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# Room temperature 9 $\mu\text{m}$ photodetectors and GHz heterodyne receivers

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Room temperature operation is mandatory for any optoelectronics technology which aims to provide low-cost compact systems for widespread applications. In recent years, an important technological effort in this direction has been made in bolometric detection for thermal imaging<sup>1</sup>, which has delivered relatively high sensitivity and video rate performance ( $\sim 60$  Hz). However, room temperature operation is still a major challenge for semiconductor photodetectors in the 8–12  $\mu\text{m}$  wavelength band<sup>2</sup>, and all developments for applications such as imaging, environmental remote sensing and laser-based free-space communication<sup>3-5</sup> have therefore had to be realised at low temperatures. For these devices, high sensitivity and high speed have never been compatible with high temperature operation<sup>6,7</sup>. Here, we show that a 9  $\mu\text{m}$  quantum well infrared photodetector<sup>8</sup>, implemented in a metamaterial made of subwavelength metallic resonators<sup>9-12</sup>, has strongly enhanced performances up to room temperature. This occurs because the photonic collection area is increased with respect to the electrical area for each resonator, thus significantly reducing the dark current of the device<sup>13</sup>. Furthermore, we show that our photonic architecture overcomes intrinsic limitations of the material, such as the drop of the electronic drift velocity with temperature<sup>14,15</sup>, which constrains conventional geometries at cryogenic operation<sup>6</sup>. Finally, the reduced physical area of the device and its increased responsivity allows us to take advantage of the intrinsic high frequency response of the quantum detector<sup>7</sup> at room temperature. By beating two quantum cascade lasers<sup>16</sup> we have measured the heterodyne signal at high frequencies, above 4 GHz. These wide band uncooled detectors shall have therefore a significant impact on technologies such as multichannel coherent Gigabit/s data transfer<sup>17</sup> and high precision molecular spectroscopy<sup>18</sup>.

37 An important intrinsic property of inter-subband (ISB) quantum well infrared photodetectors  
38 (QWIPs) based on III-V semiconductor materials that has not yet been exploited is the very short  
39 lifetime of the excited carriers. The typical lifetime is of the order of few picoseconds<sup>7</sup>, which  
40 leads to two important consequences: the detector frequency response can reach up to 100  
41 GHz, and the saturation intensity is extremely high ( $10^7$  W/cm<sup>2</sup>)<sup>19</sup>. These figures are ideal for a  
42 heterodyne detection scheme where a powerful local oscillator (LO) can drive a strong  
43 photocurrent, higher than the detector dark current, that can coherently mix with a signal  
44 shifted in frequency with respect to the LO. Notably, these unique properties are unobtainable  
45 in infrared inter-band detectors based on mercury-cadmium-telluride (MCT) alloys, which have  
46 a much longer carrier lifetime and therefore an intrinsic lower speed response<sup>2,20,21</sup>. Yet, the  
47 performance of all photonic detectors is limited by the high dark current that originates from  
48 thermal emission of electrons from the wells, and rises exponentially with temperature, thus  
49 imposing cryogenic operation ( $\sim 80$  K) for high sensitivity measurements. Previously, highly  
50 doped ( $\sim 1 \times 10^{12}$  cm<sup>-2</sup>)<sup>22</sup>, photovoltaic<sup>23</sup> 10  $\mu$ m QWIPs and QCDs<sup>24</sup> with large number of quantum  
51 wells have been observed to operate up to room temperature, but only when illuminated with  
52 powerful sources as CO<sub>2</sub> or free electron lasers.

53 In the present work, we show that this intrinsic limitation in QWIP detectors can be overcome  
54 through use of a photonic metamaterial. We are able to calibrate our detector at room  
55 temperature using a black body emitting only hundreds of nW, orders of magnitude smaller  
56 than that required previously. To date, room temperature performance with values comparable  
57 to those that we report here has only been demonstrated in the 3–5  $\mu$ m wavelength range,  
58 using quantum cascade detectors (QCDs)<sup>24-26</sup> and MCT standard detectors<sup>27</sup>.

59 The photonic metamaterial structure is shown in Fig. 1a. The GaAs/AlGaAs QWIP<sup>8</sup> contains  $N_{qw} =$   
60 5 quantum wells absorbing at 8.9  $\mu$ m wavelength (139 meV) that has been designed according  
61 to an optimized bound-to-continuum structure from ref. 7. The absorbing region is inserted in  
62 an array of double-metal patch resonators<sup>9-12</sup>, which provides sub-wavelength electric field  
63 confinement and act as antennas. The resonant wavelength is fixed by the patch size  $s$  through  
64 the expression  $\lambda = 2sn_{eff}$ , where  $n_{eff} = 3.3$  is the effective index<sup>9</sup>. The structures with  $s = 1.3$   $\mu$ m  
65 are thus in close resonance with the peak responsivity of the detector.

66 In our structure, the microcavity increases the device responsivity by a local field enhancement  
67 in the thin semiconductor absorber<sup>10</sup>, while the antenna effect extends the photon collection  
68 area of the detector,  $A_{coll}$ , making it much larger than the electrical area  $\sigma = s^2$  of the device<sup>13</sup>.  
69 As the detector photocurrent is proportional to  $A_{coll}$ , while the dark current is proportional to  $\sigma$ ,  
70 for the same number of collected photons there is therefore a substantial reduction of the dark  
71 current that results in a net increase of the detector operating temperature.

72 Besides the collection area  $A_{\text{coll}}$ , which defines the absorption cross section per patch resonator,  
73 another crucial parameter is the contrast  $C$  of the reflectivity resonance shown in Fig. **1b**. This  
74 parameter quantifies the fraction of the incident photon flux absorbed collectively by the array.  
75 As shown in Fig. **1c**, the contrast can be adjusted by changing the array periodicity  $p$ <sup>10</sup>. Optimal  
76 detector responsivity is obtained at the *critical coupling point*,  $C = 1$ , where all incident radiation  
77 is coupled into the array. The collection area per patch is related to the contrast according to  
78 the expression  $A_{\text{coll}} = Cp^2\xi$ , where the factor  $\xi = 0.7$  takes into account the polarizing effect of  
79 the connecting wires (Methods)<sup>13</sup>. From the data in Fig. **1c**, the critical coupling is obtained with  
80 a period  $p = 3.3 \mu\text{m}$ , which corresponds to a collection area  $A_{\text{coll}} = 7.5 \mu\text{m}^2$ , four times larger than  
81 the electrical area  $\sigma = 1.7 \mu\text{m}^2$  of the patch.

82 The device processing has been optimized in order to generate current solely under the metallic  
83 square patches and not below the 150 nm wide leads connecting them. To this end we have  
84 realised ohmic contacts between the patches and the underlying semiconductor layers using  
85 PdGeTiAu annealed alloy, while a Schottky barrier, made by depositing TiAu, prevents vertical  
86 current between the metallic wire and the semiconductor. Moreover, all cavities are connected  
87 to an external wire-bonding pad insulated by an 800-nm-thick  $\text{Si}_3\text{N}_4$  layer (Methods). Thanks to  
88 all these precautions the conductive area is reduced to the sum of the areas of all the patch  
89 resonators, which prevents additional dark current from flowing across the device.

90 In order to quantify the detector performance, we have compared the detector array with a  
91 reference device, here referred to as “mesa”, where the same absorbing region is processed  
92 into 200  $\mu\text{m}$  diameter circular mesa and light is coupled in through the 45°-polished substrate  
93 edge<sup>7</sup>. The mesa reference provides the intrinsic photo-response of the detector (Methods). In  
94 Fig. **2a** we compare the peak responsivities for the two configurations, obtained with a  
95 calibrated black body source at 1000°C (Methods). The mesa device could be characterized only  
96 up to 150 K, as the photo-current becomes undetectable at higher temperatures. The array  
97 detectors show a seven-fold enhancement of the responsivity at low temperatures. Most  
98 remarkably, the responsivity could be characterized up to room temperature, where the  
99 measured responsivity (0.2 A/W) is comparable with the best responsivity for the mesa device  
100 measured at around 50 K. We were thus able to record photo-current spectra up to room  
101 temperature, Fig. **2b**, which is, to our knowledge, the first type of such measurement with a  
102 QWIP operating in the 9  $\mu\text{m}$  band using a thermal source.

103 By quantifying carefully the number of photons absorbed in each geometry (Methods), we were  
104 also able to extract the photoconductive gain  $g$  for each structure (Fig. **2c**). We recall that the  
105 gain provides the number of electrons circulating per photon absorbed in the QWs<sup>7,28</sup>, and is an  
106 intrinsic property of the absorbing region. All our devices show the same values of the gain as a  
107 function of temperature, irrespective of their fabrication geometry, which proves that the

108 material properties are identical for the two structures. Following Ref.7, the photoconductive  
 109 gain is proportional to the electron drift velocity in the AlGaAs barriers and its temperature  
 110 dependence is linked to microscopic scattering processes in polar materials<sup>14,15</sup>. Our results fit  
 111 well the temperature dependence of the drift velocity described on ref. 14. The derived low  
 112 temperature value of the drift velocity is of the order of  $6 \times 10^6$  cm/s as expected at an electric  
 113 field of 20 kV/cm for an Al concentration in the range 20–30%<sup>29</sup>. These results account for the  
 114 temperature drop of the responsivity observed in Fig. 2a. Above 200 K, the gain acquires an  
 115 almost constant value  $g = 0.25 - 0.2$ , of the order of  $1/N_{qw}$ . This implies that photoexcited  
 116 electrons can only *travel* from one well to the next adjacent well, as the mean free path of the  
 117 electrons is now shorter than the distance between two wells. Very interestingly, in this limit, it  
 118 clearly appears that a detector based on a single quantum well would be advantageous at high  
 119 temperatures. These results illustrate how our devices give access to the high temperature  
 120 physics of quantum detectors, a unique regime unexplored so far.

121 The best assessment of detector performance is the specific detectivity<sup>7</sup>  $D^* = \frac{R\sqrt{A_{det}}}{\sqrt{A_{eg}I}}$  plotted in  
 122 Fig. 3a for the mesa reference and for the patch devices. The experimental results are compared  
 123 with our model that describes the impact of the photonic design on the detectivity as a function  
 124 of the temperature<sup>13</sup>. For clarity, in Fig. 3b we provide the ratio between the detectivities. At  
 125 low temperature, we observe an enhancement of only a factor of two. Here, the dark current is  
 126 negligible and the main source of noise is the background photocurrent induced by the 300 K  
 127 black body of the environment. In this regime higher responsivity means also higher background  
 128 noise, and the detectivity enhancement scales with the square root of the responsivities ratio  
 129 i.e.  $(R_{array}/R_{mesa})^{1/2} = 2.6$ . The situation is totally different at high temperature, where the dark  
 130 current is the dominant contribution to the noise. In this case the detectivity enhancement is

$$131 \quad R_{array}/R_{mesa} (A_{coll}/\sigma)^{1/2} \sim 14, \quad (1)$$

132 and the actual performance of the arrays at 300 K is equivalent to the performance of the mesa  
 133 reference at 150 K, doubling the temperature of operation. This is a significant improvement,  
 134 well beyond that is predictable from the low temperature operation. Our device concept  
 135 therefore takes advantage of both the responsivity enhancement and the strong suppression of  
 136 the dark current owing to the antenna effect, as expressed by the factor  $(A_{coll}/\sigma)^{1/2}$ . As explained  
 137 in Ref. 13, the combination of the microcavity and the antenna effect thus slows down the  
 138 decrease of the detectivity with temperature, pushing the detector operation to much higher  
 139 temperatures than expected.

140 By exploiting our photonic concepts we have achieved high temperature operation with relative  
 141 high sensitivities. We now seek to benefit from the inherent very high frequency response  
 142 together with the reduced electrical capacitance of our devices in order to use them as

143 heterodyne receivers. In this case, by increasing the power of the local oscillator one may  
144 achieve the ultimate heterodyne sensitivity set only by the detector absorption coefficient.

145 This realization is depicted in Fig. **4a**, where we show schematically the heterodyne  
146 arrangement that we used to probe our detector at room temperature. It consists of two single  
147 mode distributed feedback (DFB) quantum cascade lasers (QCLs)<sup>16</sup> operating at  $\lambda = 8.36 \mu\text{m}$ .  
148 The lasers, used respectively as signal and local oscillator are made collinear by a beam splitter  
149 (BS) before they impinge on the detector. The latter is connected via wire bonding to a high  
150 frequency coaxial cable that is connected to a spectrum analyser. Each laser has a linewidth of  
151 the order of one MHz when current and temperature are stabilised. By adjusting the  
152 temperature of each laser, their frequencies are tuned within few GHz (Methods).

153 When the detector is illuminated by both lasers a clear heterodyne signal appears on the  
154 spectrum analyser. In Fig. **4a** we show a measurement at 1.06 GHz, with a 40 dB signal-to-noise  
155 ratio. We have measured heterodyne signals up to 4.2 GHz as it is illustrated in Fig. **4b**. Our  
156 bandwidth is presently limited by a strong impedance mismatch between the detector and the  
157 external circuit. In Fig. **4c** we report the characterisation of the sensitivity of the heterodyne  
158 receiver at room temperature. The blue dots correspond to the direct current (DC) saturation  
159 curve for the LO, while the red curve is the heterodyne signal at 1 GHz as a function of the signal  
160 power. The straight line is a linear fit for the LO saturation curve. The saturation experiment  
161 shows that the detector responds linearly up to 78 mW ( $\sim 3.1 \text{ kW/cm}^2$ ) of incident power.  
162 Moreover, the linear fit intercepts the 1 Hz integration band for a power of  $\sim 0.5 \text{ nW}$ , in very  
163 good agreement with the measured room temperature detectivity from Fig. **3a**. As can be  
164 observed from Fig. **4c**, the heterodyne data are very well fitted with a square root dependence  
165 (dashed line) and can reach a signal-to-noise ratio of unity for an incident power of a few pW  
166 and an integration time of the order of 10 ms. This clearly shows the strength of the heterodyne  
167 technique that let us envision sensitivity in the thermal region at  $\lambda = 9 \mu\text{m}$  which is unreachable  
168 with any other technique at room temperature. Note that in our experiment the photocurrent  
169 induced by the LO,  $I_{\text{LO}} \sim 0.5 \text{ mA}$  is still dominated by the detector dark current,  $I_{\text{dark}} \sim 3.5 \text{ mA}$ . By  
170 increasing the LO power and/or decreasing the temperature of the detector by few tens of  
171 degrees using thermo-cooled elements, these detectors could reach the ultimate heterodyne  
172 detection limit, set by their absorption efficiency<sup>7,13</sup> and the relative intensity noise of the local  
173 oscillator<sup>30</sup>.

174 In conclusion, we have demonstrated metamaterial photonic detectors operating room  
175 temperature with high sensitivity in the second atmospheric window at  $\lambda \sim 9 \mu\text{m}$ . While our  
176 detectors show lower DC detectivity than microbolometers, they have an extremely fast  
177 frequency response of tens of GHz. Using a quantum cascade laser as a local oscillator, we  
178 have implemented a heterodyne detection setup, and validated that these uncooled detectors

179 can operate as coherent heterodyne receivers up to 4.2 GHz. The heterodyne scheme has,  
180 indeed, a tremendous potential for sensitive detection in the mid-(far-) infrared that may  
181 outperform all others competing technologies. The combination of high sensitivity with high  
182 frequency response (tens of GHz) is the essence of this new class of metamaterial detectors.  
183 Nonetheless, we recall that when installed on Peltier elements, the DC detectivity of our  
184 devices is comparable to that of uncooled microbolometers.

185 Our devices will be of extreme relevance for the detection of coherent signals (lasers), in  
186 particular for free space high-data-rate transfer<sup>17</sup> and dual comb spectroscopy<sup>31</sup>, which is an  
187 emerging high resolution spectroscopic technique, for which high speed detectors are  
188 essential. In general, well-established applications such as optical free space communications,  
189 thermal imaging and environmental remote sensing will greatly benefit from our coherent  
190 sensitive detection. Moreover, our estimates show that the heterodyne scheme could also  
191 serve for the generation and synthesis of microwaves (up to few hundreds GHz) with quite  
192 good efficiency of the order of few percent. Finally, we point out that these coherent  
193 detectors are ideally suited to be implemented into photonic integrated circuits (PIC's) where  
194 the local oscillator is combined with the heterodyne receiver.

195

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## 281 **Author contributions**

282 D.P., Y.T. and C.S. conceived the experiments, designed the QWIP structure, analysed the data  
283 and wrote the manuscript. D.P. fabricated the QWIP devices and performed measurements and  
284 data analysis together with A.B. A.M. and D.G. helped with the heterodyne measurements. A.C.  
285 calibrated the blackbody for the responsivity measurements and helped with the  
286 characterization of the mesa device. A.V. helped with data analysis. L.L., A.G.D. and E.H.L. grew  
287 the QWIP structure and provided the wafer-bonding for the double-metal processing. F.K., M.B.  
288 and J.F. provided the DFB QCLs for the heterodyne experiment. All the work has been realised  
289 under the supervision of C.S.

## 290 **Author information**

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292 The authors declare no competing financial interests.

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298 **Figure 1|Device concept.** Double-metal patch antenna, with the various metallic layers employed for  
299 electrical contacts (Methods). The absorbing region contains a QWIP structure (386 nm) with five QWs  
300 Si-doped at  $n=7\times 10^{11} \text{ cm}^{-2}$ . For this metamaterial structure the photon collection area,  $A_{\text{coll}}$ , is much larger  
301 than the electrical area  $\sigma$ . The scale bar on the image is 500 nm. **b**, Reflectivity spectrum (blue curve) of  
302 a patch antenna array with  $s=1.30 \mu\text{m}$  and a period  $p=3.30 \mu\text{m}$ . The dashed line is a Lorentzian fit  
303 providing the absorption contrast  $C$ . **c**, Contrast  $C$  and collection area  $A_{\text{coll}}$  as a function of the array unit  
304 cell area  $\Sigma=p^2$ . The observed saturation of  $A_{\text{coll}}$  is in agreement with theoretical predictions<sup>13</sup>.

305 **Figure 2|Detector characterizations.** **a**, Peak responsivity, measured with a calibrated 1000° C blackbody  
306 source, of QWIP devices fabricated in 200  $\mu\text{m}$  diameter mesa (circles), and into patch resonator arrays  
307 with  $s=1.35 \mu\text{m}$  (squares) and  $s=1.30 \mu\text{m}$  (triangles). **b**, Normalized photocurrent spectra of the  $s=1.30$   
308  $\mu\text{m}$  array at 78 K, 200 K and 295 K. **c**, Photoconductive gain and electronic drift velocity of the three  
309 devices presented in **2a** as a function of temperature, for 0.5 V bias voltage (21 kV/cm electric field ).  
310 The drift velocity is obtained using a QW capture time of 5 ps (see ref. 7 and Methods).

311 **Figure 3| Detectivity as a function of the temperature.** **a**, Specific detectivity ( $2\pi$  field of view) as a  
312 function of the temperature and at a bias of 0.5 V, for the reference mesa (circles) and two arrays  
313 structures:  $s=1.30 \mu\text{m}$  (triangles) and  $s=1.35 \mu\text{m}$  (squares). The red line is a fit of the reference using  
314  $d(T)=d_0/[1+d_1T\exp(-E_{\text{act}}/k_B T)]^{1/2}$  where  $d_0$  and  $d_1$  are fit parameters,  $E_{\text{act}} = 120 \text{ meV}$  is the activation energy  
315 and  $k_B$  is the Boltzmann constant. The blue curve is the model of quantum detectors embedded in patch  
316 resonators described in ref. 13. **b**, Ratio between the detectivities in the two different detector  
317 geometries. Dots show the corresponding BLIP temperatures:  $T_{\text{BLIP}}^{\text{mesa}} = 70 \text{ K}$  (mesa) and  $T_{\text{BLIP}}^{\text{cavity}} = 83 \text{ K}$   
318 (patch cavity arrays).

319 **Figure 4|Tunable heterodyne experiment and results.** **a**, Heterodyne arrangement involving DFB  
320 QCLs and a cavity array QWIP at room temperature . A 40 dB heterodyne power spectrum is shown,  
321 acquired using a spectrum analyser with 1 MHz resolution bandwidth. **b**, Normalized heterodyne power  
322 signal (in linear scale).. **c**, Log-log plot of the signal-to-noise ratio as a function of the signal QCL power,  
323 for LO power of 40 mW. The noise of the QWIP is calculated using the measured gain and dark current  
324 values at room temperature.

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## 333 **Methods**

334 **QWIP fabrication.** The QWIP structure is grown by MBE (molecular beam epitaxy). It consists of  
335 five GaAs quantum wells (QWs), each with a thickness  $L_{\text{QW}} = 5.2$  nm and each  $n$ -doped across  
336 the central 4 nm region with Si at a density of  $N_{\text{d}} = 1.75 \times 10^{18} \text{ cm}^{-3}$ , providing a sheet density of  
337  $n = 7 \times 10^{11} \text{ cm}^{-2}$ . The QWs are separated by  $\text{Al}_{25}\text{Ga}_{75}\text{As}$  barriers of thickness  $L_{\text{b}} = 35$  nm. At the top  
338 and bottom of this periodic structure GaAs contact layers are grown, with thicknesses  $L_{\text{c,top}} =$   
339  $100.0$  nm and  $L_{\text{c,bottom}} = 50.0$  nm and doping  $N_{\text{d,top}} = 4.0 \times 10^{18} \text{ cm}^{-3}$  and  $N_{\text{d,bottom}} = 3.0 \times 10^{18} \text{ cm}^{-3}$ ,  
340 respectively. The double-metal structures are obtained through wafer-bonding on a GaAs host  
341 substrate using 500 nm gold layers, and by selectively etching down to an etch-stop  $\text{Al}_{65}\text{Ga}_{35}\text{As}$   
342 layer grown before the bottom contact. As shown in Fig. **1a**, the patch-antennae are connected  
343 by 150 nm thin metallic wires which are realized using electron-beam lithography (consecutive  
344 alignments allow different metallic alloy contacts). The final structure is obtained by ICP etching  
345 of the semiconductor region between the antennae. The Schottky barrier under the thin  
346 metallic wires prevents vertical dark current flow between the metal and the semiconductor<sup>32</sup>.  
347 The 45° facet substrate-coupled geometry consists of a 200  $\mu\text{m}$  diameter circular mesa, with  
348 annealed Pd/Ge/Ti/Au as a top contact and annealed Ni/Ge/Au/Ni/Au as a diffused bottom  
349 contact.

350 Extended Data Fig. 1 shows a scanning electron microscope (SEM) image of the quantum  
351 detector device made of our metamaterial photonic concept. The pixel of the device is  $50 \times 50$   
352  $\mu\text{m}^2$ . The external pad is connected to the array by the 150 nm wires and is insulated from the  
353 bottom ground plane by 800 nm thick  $\text{Si}_3\text{N}_4$  layer. The TiAu pad connects the device to the  
354 external circuit by wire bonding.

355 **Reflectivity and photocurrent analysis.** Reflectivity spectra and photocurrent spectra were  
356 obtained using a Bruker Vertex interferometer. Reflectivity measurements were performed at a  
357 15° incident angle and at room temperature, and the incident light was polarized perpendicular  
358 to the 150 nm thin connecting wires. For the photocurrent spectra, QWIP devices were mounted  
359 in a cryostat with an internal cooled metallic shield and a ZnSe optical window. Photocurrent  
360 and responsivity were measured using a blackbody source at 1000 °C, which was calibrated with  
361 an MCT detector. The source is focused onto the detector by two gold parabolic mirrors ( $f/1$  and  
362  $f/3$ ), providing typical field of view of 60°. The photocurrent is measured with a lock-in  
363 technique using an optical chopper at 1059 Hz and a shunt resistance connected to the voltage  
364 input of a lock-in amplifier Stanford Research SR1830, without using pre-amplifiers.

365 **Light polarization dependence.** Our structures support two fundamental modes,  $\text{TM}_{100}$  and  
366  $\text{TM}_{010}$ , which are represented in Extended Data Fig. 2a. This figure shows the vertical electric  
367 field  $E_z$  in the plane of the resonator, obtained through finite elements simulations. The electric

368 field distribution follows a standing wave pattern, with a node in the center of the square and  
 369 maxima at the edges. The connecting wires perturb the  $TM_{010}$  mode slightly, which results in a  
 370 lower coupling efficiency for this mode. As a result, the total photoresponse of the antenna-  
 371 coupled device has a co-sinusoidal dependence with the light polarization of the normally  
 372 incident wave.

373  
 374 In Extended Data Fig. 2b, we plot the peak value of the photocurrent for a  $s = 1.30 \mu\text{m}$  structure  
 375 as a function of the polarization of a plane wave incident on the array (open circles), with the  
 376  $90^\circ$  direction corresponding to the direction of the connecting wires. The angular integral of the  
 377 cavity photocurrent peak  $I_{\text{photo}}(\theta)$  plotted in Extended Data Fig. 2b gives a polarization coupling  
 378 coefficient  $\xi_{\text{array}} = \int_0^{2\pi} I_{\text{photo}}(\theta) d\theta = 71\%$ . The contrast value  $C$  of the  $TM_{100}$  polarized light is  
 379 obtained from the measurement of Fig. 1b. For comparison, in the same graph we also plot the  
 380 polarization dependence of the photoresponse measured for the mesa geometry (open  
 381 squares). Here the  $0^\circ$  direction corresponds to the growth direction of the QWs, and the  
 382 incident wave propagates normally to the  $45^\circ$  polished facet. This polar plot therefore recovers  
 383 the inter-subband selection rule, as expected<sup>7</sup>.

384 **Definition of the collection area  $A_{\text{coll}}$ .** As all incident radiation that is not absorbed is reflected,  
 385 the contrast  $C$  provides directly the fraction between the incident  $P_i$  and absorbed flux  $P_a$  for  
 386 each patch,  $C=P_a/P_i$ . If we note by the incident photon flux  $\Phi_i$ , then the power received by each  
 387 antenna is  $P_i= \Phi_i p^2$ , and the power absorbed is by definition  $P_a= \Phi_i A_{\text{coll}}$ . Then using  $C=P_a/P_i$  we  
 388 obtain  $A_{\text{coll}} = Cp^2$ ; in the main text we also add a corrective factor of  $\xi_{\text{array}}=0.7$  owe to the  
 389 polarizing effect of the wires, as described in the previous paragraph.

390 **Responsivity, gain and specific detectivity** In Extended Data Fig. 3a we show the responsivity  
 391 curves as function of voltage for both the mesa and the patch cavity with  $s = 1.35 \mu\text{m}$ . The  
 392 decrease of the responsivity with temperature is attributed to the thermal dependence of the  
 393 charge carrier drift velocity and to an increased phonon-electron interaction<sup>14,15</sup> (see Fig. 2c).  
 394 Note that QWIP devices show the typical negative differential photoconductivity, identified as  
 395 the Gunn effect, which consists of a photocurrent decrease as function of voltage at specific  
 396 critical fields, at which inter-valley electron scattering is induced in GaAs<sup>7</sup>.

397 The responsivities of the mesa can be expressed by considering the voltage dependent  
 398 photoconductive gain  $g(T,V)$  of the detector active region and the peak inter-subband energy  
 399  $E_{21} = 143 \text{ meV}$  (taking into account many-body effects) :

$$400 \quad R_{\text{mesa}}(E_{21}, T, V) = \eta_{\text{isb}}(E_{21}) eg(T, V) t_{\text{GaAs}} \xi_{\text{mesa}} / E_{21} \quad (2)$$

401 where  $\eta_{isb} = 5.0\%$  is the absorption coefficient for the five QW system in the  $45^\circ$  facet geometry,  
 402  $e$  is the electron charge,  $t_{GaAs} = 0.67$  is the substrate transmission coefficient at  $8.6 \mu\text{m}$  and  
 403  $\xi_{mesa} = 0.5$  is the polarization factor (only one polarization of the incident light is coupled with  
 404 the  $45^\circ$  facet). Analogously to Eq. (2), we can define<sup>13</sup>:

$$405 \quad R_{array}(E_{21}, T, V) = \frac{B_{isb}(E_{21})}{B_{isb}(E_{21}) + Q_{ohm}^{-1} + Q_{rad}^{-1}} eg(T, V) C \xi_{array} / E_{21} \quad (3)$$

406 where  $Q_{ohm} = 4$  and  $Q_{rad} = 22$  represent the ohmic and radiative dissipation of the double metal  
 407 cavity, respectively, obtained by reflectivity measurements. Indeed, the Lorentzian fit of the  
 408 reflectivity resonance from Fig. 1b in the main text provides the FWHM and the sum  
 409  $1/Q_{ohm} + 1/Q_{rad}$ , and  $Q_{rad}$  is calculated from the analytical expression provided in Ref.13.

410 The dimensionless parameter  $B_{isb}$  quantifies the energy dissipation through inter-subband  
 411 absorption and is expressed by a lorentzian lineshape:

$$412 \quad B_{isb}(E) = f_w \frac{E_p^2}{4E_{21}} \frac{\hbar\Gamma}{(E - E_{21})^2 + \frac{(\hbar\Gamma)^2}{4}} \quad (4)$$

413 where  $f_w = N_{QW}L_{QW}/L = 0.067$  is the filling factor of the absorbing QWs on the overall thickness,  $E_p$   
 414  $= 47.2 \text{ meV}$  is the inter-subband plasma energy, and  $\Gamma = 15.0 \text{ meV}$  is the full-width-at-half-  
 415 maximum of the mesa photo-response, obtained by a fit to the experimental data. We obtain a  
 416 similar value  $B_{isb} = 0.07$  for the two resonant cavities  $s = 1.30 \mu\text{m}$  and  $s = 1.35 \mu\text{m}$ . The absorption  
 417 coefficient in the antenna-coupled QWIPs is described by the branching ratio  $\eta_{array} =$   
 418  $\frac{B_{isb}}{B_{isb} + Q_{ohm}^{-1} + Q_{rad}^{-1}} = 18.9\%$ . Using Eq. (2) and Eq. (3) with the measurement data in Fig. 2a, we  
 419 obtain very similar values for the photoconductive gain for the mesa and the array, as shown for  
 420 the data at  $0.5 \text{ V}$  ( $21 \text{ kV/cm}$ ) in Fig. 2a. This confirms that the absorbing regions for the two  
 421 geometries are identical. Furthermore, the data shows an exponential decrease of the gain as a  
 422 function of temperature. Following Ref. 7 the photoconductive gain can be defined as:

$$423 \quad g = \frac{\tau_{capt} v_d}{N_{QW} L_p} \quad (5)$$

424 where  $\tau_{capt} = 5 \text{ ps}$  is the capture time,  $v_d$  is the drift velocity,  $N_{QW} = 5$  is the number of quantum  
 425 wells and  $L_p = 40.2 \text{ nm}$  is the length of a period in the structure. The thermal dependence of the  
 426 gain is related directly to the drift velocity and therefore to the electron mobility. Following Ref.  
 427 14 we can express the temperature dependence as:

$$428 \quad g(T) = \frac{1}{\frac{1}{g_0} + \frac{B}{\exp\left(\frac{E_{LQ}}{k_B T}\right)} + \left(\frac{E_{AC}}{k_B T}\right)^{3/2}} \quad (6)$$

429 Here  $E_{LO}=36$  meV is the longitudinal optical phonon energy in GaAs, and the fit parameter  
430  $g_0=1.25\pm 0.03$  expresses the value of the gain at equilibrium (without thermal scattering  
431 dependence). The second term in the denominator represents the polar optical scattering (see  
432 Ref. 15) where the parameter  $B=24.4\pm 1.6$  is a dimensionless polar constant and the third term  
433 represents the deformation potential scattering caused by interaction of carriers with acoustic  
434 phonons, with a corresponding parameter  $E_{AC}=0.07\pm 0.01$  meV which characterizes the acoustic  
435 deformation potential. Eq. (6) provides very good fits of the experimental data, confirming the  
436 model.

437 The values of photoconductive gain obtained in this way are used to calculate the detectivity as  
438 function of applied voltage, at different temperatures, as illustrated in Extended Data Fig. 3b.

439 **Heterodyne measurement.** The two beams from the QCLs are made collinear using f/0.5  
440 germanium lenses and a beam splitter, and then focused onto the detector by a f/1.5 lens and a  
441  $\lambda/4$  waveplate to avoid optical feedback (Fig. 3a). The two lasers are DC biased with a voltage  
442 supply and are mounted in two Janis cryostats to stabilize their temperatures using liquid  
443 nitrogen flow. The QWIP is polarized by a Keithley 2450 sourcemeter and the heterodyne  
444 signal is sent to a spectrum analyser Agilent E4407B using a bias tee. In this arrangement the  
445 QWIP detector is at room temperature, without using any cooling system. The QC laser used as  
446 the LO is kept at a temperature 254 K while the QC laser used for the signal is kept at 293 K.  
447 With the temperature stabilized, it is possible to tune the spectral position of the two DFBs by  
448 slightly changing the applied DC current, according to the tuning coefficients  $\beta_{LO}=378$  MHz/mA  
449 and  $\beta_S=413$  MHz/mA (extracted from a linear fit to the emission frequency of the lasers as a  
450 function of temperature and bias).

451 In the case of a high power LO, the NEP of the heterodyne can be written<sup>7</sup>  $NEP_{het}=E_{21}/(\eta\tau)$   
452 where  $\eta$  is the absorption coefficient of the QWIP and  $\tau$  is the integration time (set by the  
453 integration bandwidth  $\Delta f$  as  $\tau=1/\Delta f$ ). For our device in the microcavity array we have a  
454 theoretical limit of  $NEP_{het}$  of less than 1 aW for an integration time  $\tau=1$  s at 300 K. In the  
455 experiment shown in Fig. 4, the signal-to-noise ratio is still mainly limited by the dark current.  
456 The square root fit of the signal-to-noise ratio can be extrapolated to 1, which provides  $NEP_{het}$   
457  $\sim 10$  fW for an integration time of 1 s ( $NEP_{het} \sim 1$  pW for an integration time of 10 ms), that is  
458 still four orders of magnitude higher than the theoretical limit. These estimations indicate that a  
459 high power LO could achieve sensitivities at the single photon level at room temperature.

460 **Linearity and Heterodyne Measurement** In Extended Data Fig. 4 we show the spectra of the  
461 two QCLs compared to the room temperature response of the QWIP in the microcavity array  
462 geometry. We notice that the lasers are detuned from the maximum intersubband absorption,  
463 resulting in a detector photoresponse that is half of the maximum achievable. This is an  
464 important remark because the responsivity and detectivity values we report in Figs. 2 and 3

465 correspond to the peak values of detector photoresponse. The background-limited NEP (noise  
466 equivalent power) is defined as  $NEP = \sqrt{A_{det}}/D^*$ . The detector area  $A_{det}$  corresponds to the  
467  $50 \times 50 \mu\text{m}^2$  area of the whole array, which is equal to the number of patches  $N_{patch}$  multiplied by  
468 the array unit cell area  $\Sigma = p^2$ . Indeed, in the critical coupling point, all incident radiation is  
469 absorbed by the array, and therefore the collection area for each patch  $A_{coll}$  coincides with the  
470 array unit cell  $\Sigma = p^2$ . Using our measured value of detectivity at 295 K for the cavity with  $s = 1.30$   
471  $\mu\text{m}$  at 0.5 V (Fig. 3) we have  $D^* = 2.8 \times 10^7 \text{ cmHz}^{0.5}/\text{W}$  and  $NEP = 0.2 \text{ nW/Hz}^{0.5}$ . Taking into account  
472 the 50% spectral overlap, we obtain  $NEP = 0.4 \text{ nW/Hz}^{0.5}$ , which agrees with that observed from  
473 the linearity measurement in Fig. 4c. Therefore the data presented in the main text are perfectly  
474 consistent.

#### 475 **References:**

476 **32.** Sze, S.M. and Kwok, Ng. *Physics of semiconductor devices*, Wiley, New Delhi India (2011)

#### 477 **Data availability statement**

478 The authors declare that all data supporting the findings of this study are available within the  
479 paper and its supplementary information files.

#### 480 **Extended Data Figure 1 | Global view of the device**

481 Scanning electron microscope (SEM) picture of mid-infrared QWIP structure embedded into  
482  $50 \times 50 \mu\text{m}^2$  array of patch resonators. We have indicated the top TiAu contact evaporated onto a  
483  $800 \text{ nm}$  thick  $\text{Si}_3\text{N}_4$  insulating layer.

484  
485 **Extended Data Figure 2 | Polarization dependence of the photo-response**  
486 **a**, Finite element simulation of the  $E_z$  field component coupled with the patch cavity QWIP, for  
487 the  $\text{TM}_{100}$  and the  $\text{TM}_{010}$  modes. **b**, Polar graph of the cavity photocurrent peak as function of  
488 the wire grid polarization angle. The photocurrent is normalized at its maximum at  $0^\circ$ . The open  
489 circles are the results for the cavity array, where the  $90^\circ$  direction corresponds to the  
490 connecting wires. The open squares are the results for the mesa geometry, where the  $0^\circ$   
491 direction corresponds to the growth direction of the QWs.

#### 492 493 **Extended Data Figure 3 | Mesa and cavity array detector characteristics**

494 **a**, Responsivity of the mesa and the  $s = 1.35 \mu\text{m}$  antenna-coupled devices as function of applied  
495 voltage. The temperature in K of the QWIP is indicated for each measured curve. **b**, Specific  
496 detectivity for the mesa and the microcavity devices as a function of the applied bias at  
497 different temperatures.

#### 498 499 **Extended Data Figure 4 | Spectral characteristics of the two lasers and the QWIP detector**

500 **a**, Emission spectra of the QC lasers ( $\text{QCL}_O$  and  $\text{QCL}_S$ ) compared to the room temperature  
501 response of the microcavity QWIP. **b**, Blown up version of the spectrum showing the two  
502 distinct QCL emission lines. The  $\text{QCL}_O$  was operated at  $330 \text{ mA}$  with temperature stabilized at  
503  $293 \text{ K}$ , and the  $\text{QCL}_S$  was operated at  $280 \text{ mA}$  with temperature stabilized at  $254 \text{ K}$ .









