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Mid-infrared quantum well photodetectors with 100GHz 3dB-bandwidth at room temperature

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Abstract— Ultra-fast, GaAs-based multi-quantum well photodetectors operating in the 9.5-11.5 μ m range are demonstrated, with a 3dB-cutoff bandwidth of 100GHz at room temperature. The multi quantum-well active region is sandwiched between a bottom metallic ground-plane and a top two-dimensional array of patch antennas connected in parallel. We study arrays of different dimensions and measure their frequency response in the range 0-220GHz. Beyond 100GHz we find a roll-off dominated by the 2.5ps-long, intrinsic capture time of the photo-excited electrons. To demonstrate the potential of these detectors for fast sensing applications, we show that they can be used to measure electronically and in real-time the time-dependent emission frequency of a quantum cascade laser operated in pulsed mode over a frequency range >60GHz. By exploiting broadband electronics, and thanks to its high signal-to-noise ratio, this technique allows the acquisition, in a single-shot, of frequency-calibrated, high resolution heterodyne mid-infrared spectra spanning up to 100GHz and beyond.

I. INTRODUCTION

The development of broadband mid-infrared (MIR - $\lambda=3-12\mu$ m) photo-detectors, with radio-frequency (RF) bandwidths in the tens of GHz or more, has gained momentum since the end of the 80s, following the advent of unipolar devices based on intersubband (ISB) transitions in III-V semiconductors [1]. Indeed, thanks to ultrafast electronic non-radiative recombination, these structures offer intrinsic response times in the ps range, allowing RF-bandwidths in the 100s of GHz or more, provided that the detector RC time-constant is short enough [2]. In this respect, the recent exploitation of metallic micro-antennas has opened new perspectives, allowing to shrink the detectors physical size, without compromising the quantum efficiency [3,4]. In this work we exploit this concept to demonstrate ultra-fast, patch-antenna-based GaAs-AlGaAs multi-quantum well photodetectors operating at $\sim 10\mu$ m wavelength with a 3dB-cutoff bandwidth of 100GHz at room temperature. In the second part of the work we exploit such a wide RF-bandwidth to demonstrate a gas-sensing/spectroscopy experiment based on the detection, in real-time, of the frequency down-chirp from a pulsed MIR quantum cascade laser (QCL).

II. RESULTS

The devices studied consist of sets of electrically-connected 2x2, 3x3 and 5x5 matrices of square patch-antennas, designed for detection in the 10-12 μ m wavelength range, and monolithically integrated to a 50 Ω coplanar line (Fig. 1(a)) [4]. This architecture allows direct microwave on-wafer measurements with coplanar probes, therefore removing parasitic effects due to wire-bonding/packaging. The measurement of the room-temperature frequency response (FR)

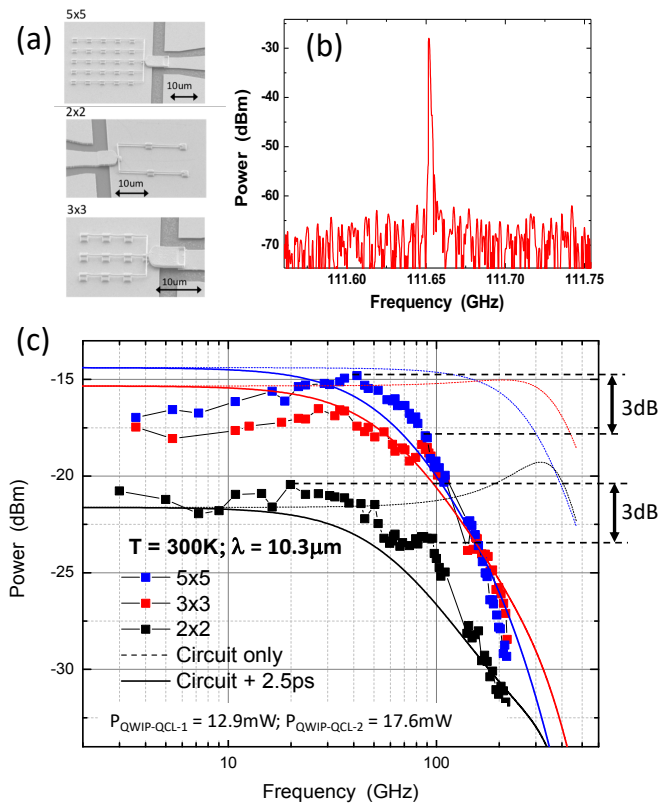


Fig. 1. (a) SEM pictures of the fabricated QWIP photodetectors. Patches are made of 1.8 μ m-side squares, electrically connected by suspended gold wires, and separated by periods of 5 μ m (5x5 and 3x3 matrices) and 10 μ m (2x2 matrix). Each patch-antenna resonator consists of a 515nm thick GaAs/Al_{0.2}Ga_{0.8}As heterostructure (seven 6.5nm-GaAs wells separated by 400-nm Al_{0.2}Ga_{0.8}As barriers) and 100nm/50nm-thick top/bottom n-doped GaAs layers, sandwiched between a bottom Au ground plane and a top Au contact layer. (b) Example of heterodyne beatnote from a 3x3 matrix QWIP, recorded at 111.6GHz with a spectrum analyzer. (c) Measured FR of QWIP photodetectors based on 5x5 (blue squares), 3x3 (red squares) and 2x2 (black squares) matrices of square patches. Dotted lines represent the computed FR of each photodetector obtained from an equivalent small-signal circuit model, based on the measured device impedances. Solid lines include the FR of the circuit, multiplied by the intrinsic material's FR, considering an electron ISB recombination time of 2.5ps.

of the devices, is obtained using a tunable extended cavity and a DFB QCLs emitting at $\sim 10.3\mu$ m, generating a photocurrent oscillating at their difference frequency (see an example of recorded heterodyne beatnote in Fig.1(b)). The latter could be continuously tuned, and was measured with two sets of coplanar probes connected to calibrated power-meters, covering respectively the 0-110GHz and 140GHz-220GHz bands, an unprecedented frequency range for quantum-well infrared photodetectors (QWIPs).

Experimental results are reported in Fig1(c), showing the FR of representative 5x5, 3x3 and 2x2 patch array photodetectors,

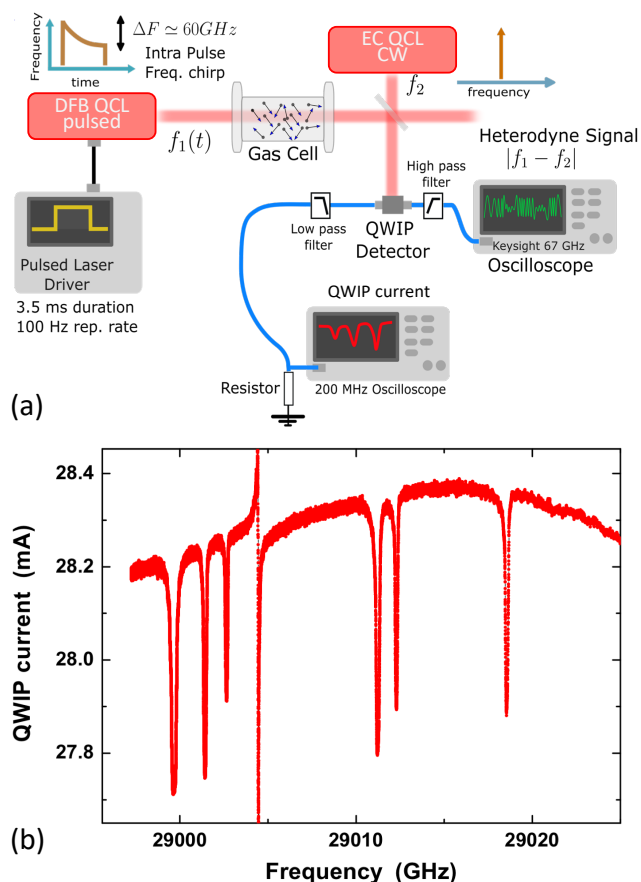


Fig. 2. (a) Experimental setup used for the self-frequency calibrated, real-time, chirped-pulse spectroscopy of NH_3 (see main text). (b) Experimental spectrum of NH_3 , showing 6 rovibrational transitions (the fourth peak starting from the left is an artifact of the measurement technique).

measured at 300K with a total incident QCL power of $\sim 30\text{mW}$. The different RF power levels reflect the different dc -responsivities and impedances of the devices. We obtain 3dB cutoffs of 90GHz (5x5 matrix) and 100GHz (3x3 and 2x2 matrix), the highest reported to date for photodetectors based on ISB transitions [1-4]. The FR derived from a small-signal circuit model, where the ac current source is based on the measured photocurrents is shown by the dotted-line curves. Clearly, by comparing with the experimental curves, we find that the QWIPs FR is not limited by the circuit itself. A much better agreement with the data is given by the solid curves, obtained by multiplying the electrical FR by the intrinsic FR of the ISB system, corresponding to a single exponential photocurrent decay-time of $\sim 2.5\text{ps}$, that we identify as the electron's capture time.

As an example of application of the demonstrated ultrafast MIR QWIPs, in Fig. 2(a) we report an experimental setup used for the detection of ammonia, based on heterodyne MIR mixing. A DFB QCL emitting at $\sim 10.3\mu\text{m}$ wavelength illuminates the gas cell, and is operated in pulsed mode, generating a thermally driven down-chirp of the emission frequency of approximately 60GHz [5]. The latter is detected by heterodyne mixing with an external cavity (EC) QCL operated in CW, using a 5x5 QWIP photodetector connected to a 67GHz real-time oscilloscope (the emission frequency of the

external cavity QCL is measured with a MIR lambda-meter – not shown in Fig.2(a)). Fourier transforming the so obtained single-shot, heterodyne pulses yields the instantaneous DFB QCL frequency. The latter can then be used to obtain the frequency scale of the transmission spectrum of NH_3 , recorded by measuring the QWIP photocurrent vs time using a standard 200MHz oscilloscope. An example of spectrum of ammonia centered around 29010GHz ($10.34\mu\text{m}$) and spanning $\sim 25\text{GHz}$ is shown in Fig.2(a).

III. SUMMARY

MIR unipolar photodetectors with a 3dB-bandwidth of 100GHz at room temperature are demonstrated. We believe that these devices will open up new perspectives for a number of applications, from coherent gas-sensing/spectroscopy to free-space communications, light-detection and ranging (LIDAR) and astrophysics [5-10].

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