Accurate modelling and measurement of the impedance match between UTC photodiodes and THz antennas

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***Abstract*—Maximising the power extracted from UTC photodiodes is central to the successful realisation of photonic terahertz emitters. For antenna integrated UTCs this requires the optimisation of the impedance match between UTCs and antennas. We present a comprehensive investigation of the UTC output impedance up to 400 GHz, by means of a semi-analytical approach and using 3D full-wave modelling. We introduce a new, accurate, UTC circuit model, exhibiting very good agreement with the measurements. By properly taking into account the UTC-to-antenna impedance match, we demonstrate successful prediction of the absolute level of power radiated by a bow-tie antenna integrated UTC.**

I. Introduction

PHOTONIC THz emitters, based on antennas integrated with UTC photodiodes [1-3], are promising candidates for the realisation of compact and efficient continuous-wave sources within the lower part of the THz spectrum (100 GHz – 3 THz). Current research on antenna integrated UTC-PDs is focused on increasing the emitted power and bandwidth. Emitted power and bandwidth depend on 4 key factors: 1) optical fibre to chip coupling efficiency; 2) photodiode bandwidth and optical responsivity; 3) photodiode to antenna coupling efficiency; 4) antenna directivity and radiation efficiency. Point 3 (photodiode to antenna coupling efficiency) has not received much attention in the literature. To optimise the efficiency of power coupling between UTCs and antennas, complex-conjugate matching needs to be realised. Therefore it is essential to know the real part (resistance) and imaginary part (reactance) of the UTC output impedance over the frequency range.

II. Results

We performed a detailed analysis of UTC photodiode impedance and found that the classical diode circuit model [4], based on the junction-capacitance/series-resistance concept, cannot explain the experimental data, especially in the lower frequency range (DC to 30 GHz) where parasitic effects are negligible and hence cannot be used to explain the disagreement. We characterised several UTC-PDs up to 110 GHz. We propose a new circuit model (Fig. 1), to explain the observations [5], that achieves very good agreement with the measurements. A link is suggested between the additional energy storage circuit elements present in the new circuit and quantum mechanical effects taking place between the UTC absorption and collection layers (i.e. through the spacer layers). We also performed 3D full-wave modelling of detailed UTC photodiode structures, as shown in Fig. 2, to achieve accurate knowledge of the UTC output impedance up to 400 GHz [6]. The model is very detailed, e.g. the extremely thin (less than 20 nm) spacer layers, shown in Fig. 1, were discretized by 4 mesh lines in the vertical direction. The S_{11} and impedance of a 3 x 15 µm^2 area UTC, at 2 V reverse bias, were calculated using CST Microwave Studio software up to 400 GHz and are shown in Fig. 3, together with the experimental data up to 110 GHz and the results obtained using the new equivalent circuit shown in Fig. 1 [3].

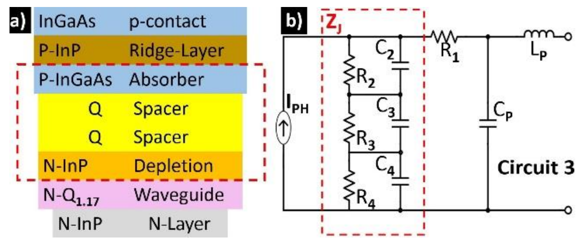

Fig. 1. (a) UTC layer structure. (b) New equivalent circuit, showing the relation with the UTC structure. The two spacers have been modelled as two *RC* parallel circuits (R_2C_2 and R_3C_3). The R_4C_4 parallel represents the carrier collection layer, while R_1 takes into account the resistive effects of doped materials and ohmic contacts. C_P and L_P account for parasitic effects.

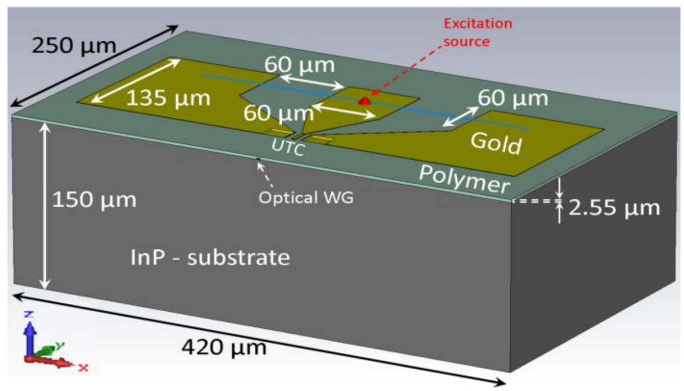

Fig. 2. CST model including the whole of the cleaved chip and the CPW pads.

The values of the circuit parameters in Fig. 1 are the following: R_1=15Ω, R_2=265Ω, C_2=85fF, R_3=125Ω, C_3=70fF, R_4=300kΩ, C_4=60fF, C_P=1fF, L_P=16pH. The value of 16 pH for L_P results from fitting the S_{11} measured in the W-band. We investigated the effect of the Coplanar Waveguide (CPW) pads on the S_{11} both experimentally and using CST. We found that the CPW pads have no or small effect on the S_{11} below 67 GHz, whereas they start having a significant effect in the W-band; the effect becomes dramatic above 110 GHz. The CST modelled S_{11} and impedance shown in Fig. 3 have been calculated in CST excluding the effect of the CPW pads and therefore refer to the UTC alone. This is important in view of the UTC to antenna matching optimisation, since the impedance seen from the terminals of an antenna integrated with the UTC does not include the CPW pads. The magnitudes of the measured S_{11} and the S_{11} obtained with CST and the equivalent circuit are all in excellent agreement up to 90 GHz and good agreement between 90 GHz and 110 GHz. The phases are all in excellent agreement up to 67 GHz, then measurement and circuit phases maintain good agreement up to 110 GHz, while CST phase begins to depart. Above 110 GHz the disagreement between the equivalent circuit and CST S_{11} becomes increasingly significant. This disagreement is entirely due to the value of the inductance L_P in the circuit which is too high (16 pH). Importantly, if L_P is reduced to 6.5 pH, the S_{11} and impedance obtained with CST and the circuit are identical up to 400 GHz. The value of 16 pH for L_P resulted from the need to force the circuit S_{11}, particularly its phase, to match the S_{11} measured between 75 GHz and 110 GHz. However the S_{11} measured in the W-band is affected by the effect of the CPW and most importantly by inevitable uncertainty of on-wafer calibration at these frequencies [7].

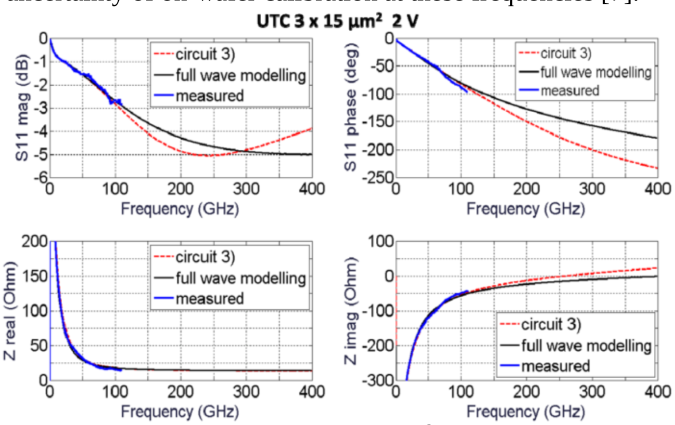

Fig. 3. S_{11} and impedance of the 3 x 15 µm^2 area UTC at −2 V bias, calculated using CST, compared with the experimental data and with the results obtained using the equivalent circuit (including the overestimated parasitic inductance L_P= 16 pH). The amended value of 6.5 pH for L_P provides excellent agreement between circuit and CST up to 400 GHz.

We demonstrate successful prediction of the absolute power radiated by a bow-tie antenna integrated UTC (Fig. 4) by means of 3D full-wave modelling and using the knowledge of the UTC output impedance to take the UTC-to-antenna

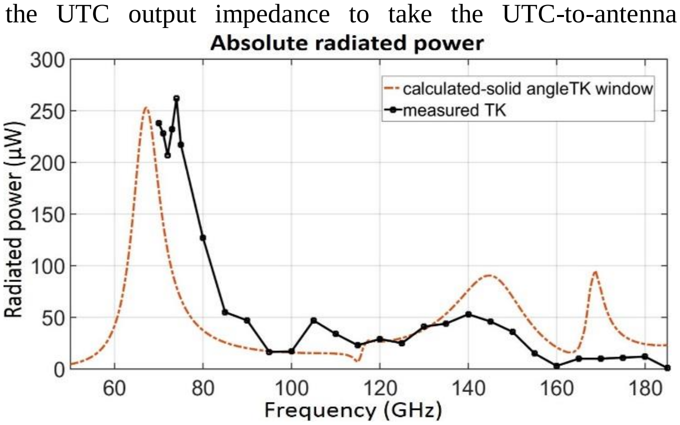

Fig. 4. The dash-dot curve is the absolute radiated power calculated with 3D full-wave modelling. The continuous black curve represents the absolute radiated power measured with a Thomas Keating (TK) power meter; the measurements were not performed above 185 GHz as the detected signal reached the minimum level detectable by the TK power meter.

coupling efficiency into account. We also found that, when the UTC-to-antenna coupling efficiency is modelled using the classical junction-capacitance/series-resistance concept, calculated and measured radiated power are in substantial disagreement. The ability to calculate the absolute radiated power correctly, will enable us to maximise it through optimisation of the UTC-to-antenna impedance match.

III. Conclusions

Design of optimised antennas for integration with UTCs requires accurate knowledge of the complex UTC source impedance in order to achieve maximum radiated power. The maximisation of the power extracted from a UTC is central to the successful realisation of a photonic THz emitter. When the UTCs are integrated with antennas, such maximisation entails the optimisation of the energy coupling between UTC and antenna. This aspect of antenna integrated UTCs has not received much attention in the literature. In this work we have carried out a semi-analytical investigation of the impedance of waveguide UTCs, supported by experimental data taken up to 110 GHz and circuit analysis. We have performed for the first time 3D full-wave modelling of a detailed UTC-PD structure, including all epitaxial layers, and calculated the UTC impedance up to 400 GHz. We have provided evidence, for the first time, that proper evaluation of the UTC impedance and UTC-to antenna impedance match can allow accurate calculation of the absolute power radiated by an antenna integrated UTC over the frequency range. We have demonstrated successful prediction of the absolute emitted power by modelling and measuring a bow-tie antenna integrated UTC up to 185 GHz. The capability of calculating the absolute emitted power correctly raises the possibility to maximise the radiated power via optimisation of UTC-to-antenna impedance match. We can effectively design antennas with ad hoc complex impedance, realising complex-conjugate matching with the UTC.

IV. Acknowledgments

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References

[1]. A. J. Seeds, M. J. Fice, K. Balakier, M. Natrella, O. Mitrofanov, M. Lamponi, M. Chtioui, F. van Dijk, M. Pepper, G. Aeppli, a. G. Davies, P. Dean, E. Linfield, and C. C. Renaud, "Coherent terahertz photonics," *Optics Express*, vol. 21, pp. 22988-23000, 2013.

[2]. E. Rouvalis, C. C. Renaud, D. G. Moodie, M. J. Robertson, and A. J. Seeds, "Traveling-wave Uni-Traveling Carrier photodiodes for continuous wave THz generation," *Optics Express*, vol. 18, pp. 11105-11110, 2010.

[3]. T. Ishibashi, Y. Muramoto, T. Yoshimatsu, and H. Ito, "Uni-Traveling-Carrier Photodiodes for Terahertz Applications," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 20, pp. 79-88, 2014.

[4]. G. Lucovsky, M. E. Lasser, and R. B. Emmons, "Coherent Light Detection in Solid-State Photodiodes," *Proceedings of the IEEE*, vol. 51, pp. 166-172, 1963.

[5]. M. Natrella, C.-P. Liu, C. Graham, F. van Dijk, H. Liu, C. C. Renaud, and A. J. Seeds, "Accurate equivalent circuit model for millimetre-wave UTC photodiodes," *Opt. Express*, vol. 24, no. 5, pp. 4698–4713, 2016.

[6]. M. Natrella, C.-P. Liu, C. Graham, F. van Dijk, H. Liu, C. C. Renaud, and A. J. Seeds, "Modelling and measurement of the absolute level of power radiated by antenna integrated THz UTC photodiodes," *Opt. Express*, vol. 24, no. 11, p. 11793, 2016.

[7]. A. J. Lord, "Comparing the accuracy and repeatability of on-wafer calibration techniques to 110GHz," *Microw. Conf. 1999. 29th Eur.*, vol. 3, pp. 28–31, 1999.