THERMAL PHASE LAG HETERODYNE INFRARED IMAGING FOR CURRENT TRACKING IN RADIO FREQUENCY INTEGRATED CIRCUITS

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Abstract

With thermal phase lag measurements, current paths are tracked in a Class A Radio Frequency (RF) power amplifier at 2 GHz. The amplifier is heterodynally driven at 440 MHz and 2 GHz, and its resulting thermal field respectively inspected at 1013 and 113 Hz with an infrared lock-in thermography system. The phase lag maps evidence with a higher sensitivity than thermal amplitude measurements, an input-output loop due to a substrate capacitive coupling. This limits the amplifier's performance, raising the power consumption in certain components. Other information relative to local power consumption and amplifier operation is also inferred. This approach allows the local non-invasive testing of integrated systems regardless of their operating frequency.

Layout studies in Radio Frequency (RF) Integrated Circuits (ICs) are crucial to understanding their performance limits¹ and ageing effects.^{1,2} Traditionally, the IC local behavior has been inferred from high level electrical figures of merit; which requires expensive equipment, complex tests, and access to internal nodes with frequency adapted pads.^{3,4,5} Unfortunately, this approach cannot always determine intradie parasitic couplings responsible for high frequency undesired current paths, whose detection and prevention is a cornerstone in RF ICs analog design (mainly in power amplifiers).^{1,6,7} Such paths can limit the IC frequency response and power delivered to the load, giving rise to overloading conditions and eventually, the IC failure.⁸ To identify them, an innovative and efficient solution is its local tracking through the IC under operation. In this regard, using off-chip thermal imaging systems (e.g., Infrared Lock-In Thermography⁹ –IR-LIT–, thermorefectance¹⁰, or MOSFET hot-carriers’ luminescence¹¹) is very promising.^{12,13,14,15,16,17} They noninvasively sense the heat generated while the IC is under operation. Besides, the Joule effect allows converting electrical information from a high frequency f into a thermal field at a lower frequency Δf (heterodyne detection) within the imaging system bandwidth.^{13,17,18,19} Currently, such techniques are only employed for failure analysis and debugging,^{13,17,18,20,21,22,23,24} whereas maximum frequencies of 30 MHz in test structures¹⁹ and around 14 MHz in IC powering systems¹⁷ have been reported. They only monitor the thermal amplitude of hot spots, where thermal phase lag only assists to locate them through the following criterion: a maximum in amplitude and a minimum in phase lag should be detected at the same place.^{17,19} As a new application scenario, this work proposes tracking the current paths in more complex systems (RF ICs) operating within GHz range by thermal phase lag measurements. In comparison with amplitude monitoring, phase lag is surface emissivity independent⁹ and more sensitive to heat sources detection (thermal activity)

when synchronized with a driving electrical signal.

To illustrate this, let us consider an IC with N devices located on top of a semiconductor die at several positions $\vec{r}_i$. The IC input is driven with a voltage $V_{\text{gen}}(t)$, which allows heterodyne excitation, i.e.: $V_{\text{gen}}(t) = V_{\text{gen},0}(\cos(2\pi f_1 t) + \cos(2\pi f_2 t))$ such that $\Delta f = f_1 - f_2 \ll f_1, f_2$ and $f = f_1 \approx f_2$. These devices may behave as thermally interacting heat sources and leading to a total thermal field $\Delta T(\vec{r}, t)$ at any given location on the die surface $\vec{r}$. The i -th heat source withstands a voltage drop $V_i(f)$ and current $I_i(f)$, and dissipates, due to Joule effect, a real power spectral component at Δf $P_i(t)$.¹⁹

$$P_i(t) = |V_i(f)| |I_i(f)| |\cos(\eta_i(f))| \cos(2\pi \Delta f t + \vartheta_i + \chi) \quad (1)$$

where $\eta_i(f)$ is the electrical phase lag between $V_i(f)$ and $I_i(f)$, ϑ_i corresponds to the phase lag of the heat generated (or power dissipated) between each heat source (or device), and χ provides the phase lag respect to $V_{\text{gen}}(t)$. Thus, the i -th heat source generates a thermal field spectral component at Δf $[\Delta T_i(|\vec{r} - \vec{r}_i|, \Delta f)]$ with an amplitude $|\Delta T_i(|\vec{r} - \vec{r}_i|, \Delta f)|$ and phase lag $\theta_i(|\vec{r} - \vec{r}_i|, \Delta f) + \vartheta_i$. When all heat sources thermally interact, the amplitude and phase lag of the spectral component at Δf of the thermal field resulting from their thermal interaction $[|\Delta T(\vec{r}, \Delta f)|$ and $\phi_\tau(\vec{r}, \Delta f)$, respectively] writes as:

$$\begin{aligned} |\Delta T(\vec{r}, \Delta f)| = & \left[\sum_{i=1}^N |\Delta T_i(|\vec{r} - \vec{r}_i|, \Delta f)|^2 \right. \\ & + 2 \sum_{i \neq l}^N |\Delta T_i(|\vec{r} - \vec{r}_i|, \Delta f)| |\Delta T_l(|\vec{r} - \vec{r}_l|, \Delta f)| \cos[\theta_i(|\vec{r} - \vec{r}_i|, \Delta f) + \vartheta_i \\ & \left. - (\theta_l(|\vec{r} - \vec{r}_l|, \Delta f) + \vartheta_l)] \right]^{1/2} \end{aligned} \quad (2)$$

$$\phi_\tau(\vec{r}, \Delta f) = \tan^{-1} \left[\frac{\sum_{i=1}^N |\Delta T_i(|\vec{r} - \vec{r}_i|, \Delta f)| \sin(\theta_i(|\vec{r} - \vec{r}_i|, \Delta f) + \vartheta_i)}{\sum_{i=1}^N |\Delta T_i(|\vec{r} - \vec{r}_i|, \Delta f)| \cos(\theta_i(|\vec{r} - \vec{r}_i|, \Delta f) + \vartheta_i)} \right] \quad (3)$$

where equations (1)-(3) link $|\Delta T(\vec{r}, \Delta f)|$ and $\phi_\tau(\vec{r}, \Delta f)$ to the high frequency electrical signals flowing through each device. For reliable lock-in measurements, both $\phi_\tau(\vec{r}, \Delta f)$ and χ are mandatory to be stable or noiseless, even when low or null $|\Delta T(\vec{r}, \Delta f)|$ is detected. When given, this situation points out a certain thermal activity or heat generation in correlation with the reference signal $V_{\text{gen}}(t)$; and $\phi_\tau(\vec{r}, \Delta f)$ measurements can indicate current paths (whenever thermal activity is detected) and power flows (i.e., absorbed –positive– or delivered –negative– power from the biasing source)²⁵. In Eq. (1), when ϑ_i is only induced by $\eta_i(f)$, $\vartheta_i = \cos^{-1}[\text{sgn}(\cos(\eta_i(f)))]$ is fulfilled, where $\text{sgn}(\cos(\eta_i(f)))$ is the sign function of $\cos(\eta_i(f))$. Therefore, ϑ_i can only be 0 or π rad. This extremely affects the spatial response of $\phi_\tau(\vec{r}, \Delta f)$, as $\theta_i(|\vec{r} - \vec{r}_i|, \Delta f)$ has a weaker dependence on $|\vec{r} - \vec{r}_i|$. Consequently, $\phi_\tau(\vec{r}, \Delta f)$ spatial profiles present an abrupt transition with a large signal variation, which enhances the measurement dynamic range, as in the thermal gradient monitoring,¹⁴ and provides a higher immunity to noise than those of $|\Delta T(\vec{r}, \Delta f)|$.²⁶ As a proof of concept, this work proposes to locally study by IR-LIT the current paths of a Class A RF power amplifier at $f = 2$ GHz to determine an input-output loop due to a substrate capacitive coupling. IR-LIT has been selected because of its commercial availability, minimum requirements in sample preparation, thermal sensitivity,¹⁴ and capability of carrying out heterodyne detection.¹⁹

Figure 1 depicts the schematic (a) and the layout (b) of the power amplifier under study: 2 transistors in a cascode topology, with an isolated DC output and an L-C band input (implemented in Figure 1 with L_{in} and C_{in}) frequency tuning. The transistors role in the amplifier is the following. M_1 is a DC self-biased (through resistor R_1) transistor in common source, which converts the applied input gate voltage into an output drain

current to reach the amplifier power gain required in the load (e.g., antenna). By contrast, M_2 , in common gate, isolates the output node and M_1 .²⁷ This amplifier has been fabricated in 0.35 μm 2P4M (2 levels of polysilicon, 4 levels of metal) Complementary Metal-Oxide-Semiconductor (CMOS) technology onto a 725 μm thick substrate and tuned at a central frequency $f_{c,G} = 440$ MHz. For the experiments, the amplifier input has been heterodynnally driven with an Agilent E4438C ESG Vector Signal Generator (total input power $|P_{\text{in,het}}|$ of 0.5 mW), and a FLIR SC5500 IR camera has been employed for thermal acquisitions. A frame rate of 376 Hz and an integration time of 1200 μs have been considered (i.e.: 2.5×10^4 images processed at Δf). To improve the signal to noise ratio (SNR) during IR measurements, the die, attached to a specifically-designed RF board, has been placed on a micropositioning stage thermo-regulated with a Peltier system and its operating temperature T_i has been set for 60°C. As a result, the maps of $|\Delta T(\vec{r}, \Delta f)|$ and $\phi_\tau(\vec{r}, \Delta f)$ (referred to as $|\Delta T|$ and ϕ_τ) were derived. The so-called $|\Delta T|$ apparent maps ($|\Delta T|_{\text{app}}$) have been also used, as they allow straightforward analyzing the electrical behavior when IC locations or areas with the same surface emissivity are considered.

The capacitive input-output loop has been studied by comparing $|\Delta T|_{\text{app}}$ at $f = f_{c,G}$ [Figure 2 (a)] with $|\Delta T|_{\text{app}}$ and ϕ_τ at $f = 2$ GHz [Figures 2 (b) and (c), respectively] setting the appropriate Δf in each case. For $f = f_{c,G}$, $\Delta f = 1013$ Hz was selected to confine the thermal field around the heat sources, whereas for $f = 2$ GHz, $\Delta f = 113$ Hz was set to obtain during IR-LIT acquisitions, an optimum SNR ensuring the measurement independence from boundary conditions.^{14,19} Amplitude results are first used to identify which amplifier devices behave as hot spots at two different frequencies. As explained latter, phase measurements will assist in determining high frequency parasitic capacitive couplings which are not appearing at the central frequency. For this reason, ϕ_τ at

$f = 440$ MHz is not provided. In Figure 2 (a), transistors M_1 and M_2 , jointly with the capacitor $C_{\text{ext},2}$ (power delivered to the output), are the components with higher consumption during regular operation. This contrasts with Figure 2 (b) where L_{in} and M_2 are the main heat sources, as also observed in ϕ_τ map [Figure 2 (c)]. This indicates that at $f = 2$ GHz, i_{in} is mainly diverted across a capacitive coupling path [Path A], while that expected without any input-output loop [Path B] is still thermally detectable. To better interpret such results, a high frequency small-signal equivalent circuit has been inferred in Figure 2 (d) for Paths A (in solid blue) and B (in dashed red). These qualitative description considers: the L_{in} series resistance ($R_{L\text{par}}$), transconductance g_{m,M_m} for each transistor (i.e., $m=1, 2$), which relates the drain current $i_{D,m}$ with the gate to source voltage $v_{gs,m}$, and its parasitic capacitances (i.e., gate to drain, C_{gdm} , and gate to source, C_{gsm})²⁸. In Figures 2 (b) and (c), Path A is observed below C_{in} and between the hottest areas corresponding to L_{in} and M_2 . Additionally, other local heat sources (HS_1 and HS_2) appear. HS_1 corresponds to the interconnecting via between metal levels 3 and 4 in L_{in} , whereas HS_2 locates a hot spot along the connection track (metal level 3) between L_{in} and C_{in} only observable as a local minimum in ϕ_τ map. These results differently reveal the origin of the $L_{\text{in}}\text{-}M_2$ capacitive path when the substrate equivalent impedance [R_{subs} in series with C_{subs} , Figure 2 (d)] decreases with f . In $|\Delta T|_{\text{app}}$ map, the coupling is mostly located between HS_2 and M_2 (below C_{in}) and between HS_1 and M_2 , showing a noisy spatial acquisition. By contrast, a larger area in figure 2 (c) depicts the coupling in ϕ_τ map with a much better spatial SNR. On the other hand, Path B is pointed out only in ϕ_τ map [Figure 2 (c)], where HS_2 and C_{in} thermal activities are detected (local minimum in ϕ_τ reached). When $|\Delta T|_{\text{app}}$ is practically null in some IC components (e.g., R_2 , $C_{\text{ext},1}$, R_1 , C_{in} or M_1), additional information can be extracted from ϕ_τ maps with a higher dynamic range, e.g., $R_2\text{-}C_{\text{ext},1}$ branch, R_1 , C_{in} and M_1 are thermally active. This

evidences an extremely low current level (almost negligible) passing across them, as the power consumption in such components is practically null according to $|\Delta T|_{\text{app}}$ map. Consequently, at $f=2.0$ GHz, i_{in} mostly passes across L_{in} and M_2 , avoiding M_1 . Accordingly, the following can be inferred: when i_{in} starts to divert through Path A, $V_{\text{gs}1}$, and consequently, $V_{\text{ds}1}$ and $V_{\text{sg}2}$, decrease, lowering the power dissipated by M_1 [Figures 2 (c) and (d)]. On the contrary, M_2 conducts both the currents from Paths A and B, as it operates as a cascode (resistor-like element) extremely increasing its heat dissipation [Figures 2 (c) and (d)]. Simultaneously, the impedance in L_{in} increases with frequency, which enlarges its voltage drop or $v_{\text{L,par}}$ [Figures 2 (b), (c), and (d)], and consequently, its power dissipation.

Thanks to the higher sensitivity and larger dynamic range of ϕ_τ measurements, deeper details can be deduced about the IC power flow and M_2 - L_{in} coupling. Figure 3 depicts a ϕ_τ map superposed to the IC layout (a), reporting two ϕ_τ profiles: the former along M_1 and M_2 [(b), referred to as $\phi_\tau|_{M_2}$], and the latter between both transistors and L_{in} [(c), referred to as $\phi_\tau|_{L_{\text{in}}}$]. Moreover, Figure 3 (c) presents a data averaging performed for $x < 360$ μm (black solid lines) to illustrate the sensitivity of this approach for a spatial noisy acquisition. With regards to the power flow, $\phi_\tau|_{M_2}$ points out without any spatial filtering, an abrupt transition coincident with the M_1 placement, and its minimum is aligned with M_2 location, i.e., the main heat source along $\phi_\tau|_{M_2}$ [Figure 3 (b)]. According to the presented theory, this steep variation is consequence of $\vartheta_{M_1} - \vartheta_l = \pi$ rad (l refers to any other IC component), and only occurs when $\eta_{M_1} = \pi$ rad and $\vartheta_{M_1} \gg \vartheta_l, \theta_{M_1}, \theta_l$. Therefore, M_1 is still delivering electrical power from the biasing sources to the rest of IC components, though the heat generation is very low as derived from $|\Delta T|_{\text{app}}$ map [Figure 2 (b)]. This is confirmed with the behavior of other IC components thermally active in Figure 3 (a), which are almost at the same

ϕ_τ than M_2 . As for L_{in} - M_2 coupling, $\phi_\tau|_{L_{in}}$ presents a local relative minimum between HS_1 and HS_2 [Figure 3 (c)], which indicates the parasitic path position in the IC [necessary condition according to Eq. (3)]. The local modulation in $\phi_\tau|_{L_{in}}$ minimum observed in Figure 3 (c) allows correlating not only the HS_1 and HS_2 locations with layout interconnecting elements, but also the track vias to C_{in} (via, C_{in}) and L_{in} output (via) in HS_2 . According to this figure, HS_1 , HS_2 , and track vias in HS_2 are the leakage current spots responsible for the substrate capacitive coupling.

ϕ_τ also allow studying the thermal range between heat sources to consider whether they interact. $\phi_\tau|_{M_2}$ and $\phi_\tau|_{L_{in}}$ show for $x \geq 360 \mu\text{m}$, a linear trend on lateral position x , whose slope follows the equation:¹⁹

$$\alpha = 1/L_D = \sqrt{\pi \Delta f / D_\alpha} . \quad (4)$$

α corresponds to the inverse of the thermal characteristic length L_D defining the heat confinement radius around a non-interacting heat source, and D_α is the Silicon thermal diffusivity ($85.49 \pm 2.41 \text{ mm}^2 \text{ s}^{-1}$, used in this work).²⁹ According to this D_α value and Eq. (4), α is $(2.04 \pm 0.06) \times 10^{-3} \mu\text{m}^{-1}$, which perfectly agrees with that experimentally inferred from Figures 3 (b) and (c) (α_1 and α_2 , respectively). This reveals two important conclusions on spatial noise and thermal interaction range. Firstly, even in the noisiest ϕ_τ interval [highlighted in grey in Figures 3 (b) and (c)], experimental data still follow such linear behavior expected when non-interacting punctual heat sources within an infinite media are dissipating power.^{14,19} Thus, by employing behavioral modeling, increasing camera acquisition time, or even using a low pass filter, spatial noise in ϕ_τ can be overcome. Secondly, this criterion should be different when heat sources

interact, as deduced from Figure 3. In Figure 3 (b) around M_2 location, $\phi_\tau|_{M_2}$ has another slope α'_D (in solid blue) whose inverse provides a new characteristic length $L'_D = 258 \mu\text{m}$. This distance can be a new criterion to discriminate purely thermal interacting heat sources (i.e., substrate heat diffusion). From visual inspections in Figure 3 (a), the location of all IC parts can be deduced at shorter distances than those indicated above (approximately $40 \mu\text{m}$ or less). According to this, the distances between $HS_2 - M_2$ and $HS_1 - M_2$ ($270 \mu\text{m}$, approximately) are long enough to detect a relative minimum in $\phi_\tau|_{L_{in}}$ originated by a heat source caused by a substrate current.

As another interesting result, the real power averaged over L_{in} and M_2 ($|\bar{P}|_{L_{in}}$ and $|\bar{P}|_{M_2}$, respectively) at $f = 2 \text{ GHz}$ can be estimated gathering ϕ_τ and $|\Delta T|$ results with electrical measurements of a virtual network analyzer (ZVM Rohde & Schwarz). First, the output power ($35 \mu\text{W}$) and reflected input power coefficient (15%) at $f = 2 \text{ GHz}$ are required. With these values, it can be calculated that 71% of $|P_{in,het}|/2$ (a half of $|P_{in,het}|$ per f_1 and f_2) is mainly dissipated into heat in L_{in} and M_2 [according to Figures 2 (b) and (c)]. Next, from the thermal amplitude averaged in L_{in} ($|\overline{\Delta T}|_{L_{in}}$) and M_2 ($|\overline{\Delta T}|_{M_2}$), $|\bar{P}|_{L_{in}}$ and $|\bar{P}|_{M_2}$ ($|\bar{P}|_i$, where $i = L_{in}$ or M_2) can be extracted with the following expression:

$$|\bar{P}|_i = \frac{|\overline{\Delta T}|_i}{|\overline{\Delta T}|_{L_{in}} + |\overline{\Delta T}|_{M_2}} 0.71 |P_{in,het}|/2 \quad (5)$$

where $|\bar{P}|_i = \kappa |\overline{\Delta T}|_i$ with the same κ for each device is assumed in a first approximation. Thus, taking into account $|\overline{\Delta T}|_{L_{in}}$ and $|\overline{\Delta T}|_{M_2}$ at $f = 2 \text{ GHz}$ and $|P_{in,het}|/2$ (i.e., $|P_{in,het}|/2 = 250 \mu\text{W}$); $|\bar{P}|_{L_{in}}$ and $|\bar{P}|_{M_2}$ are 76.3 ± 15.4 and $101.1 \pm 20.5 \mu\text{W}$, respectively. Such values are not high enough to induce the amplifier failure, but in another case, the IC proper operation could be compromised.

In summary, ϕ_τ maps allow an on-line characterization of current paths and IC parts with a higher resolution than $|\Delta T|$ maps. ϕ_τ can be used to improve the IC reliability and performances by design, or to locate the parts of the IC layout responsible for a yield drop. Another benefit when combined with $|\Delta T|$ measurements is not only the capability of inferring small-signal equivalent models by tracking current paths, but also to gain insight into the IC electrical behavior and quantitatively determine the components power consumption at any working frequency. This shows a great potential in future studies dealing with amplifier efficiency, induced overloading conditions in IC blocks, and other issues due to the connection tracks. Besides, this approach can be extended to other applications regardless of their working frequency, as for instance, the microstrip filters characterization.

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Figures & Captions:

Figure 1. (a) Schematic of the cascode power amplifier analyzed. (b) Layout view of power amplifier, highlighting its in/output pads and pinout, main interconnection tracks (power supply, V_{DD} , Ground, V_{SS} , input, V_{in} , and output, V_{out}), active (M_1 and M_2) and passive (C_{in} , L_{in} , $C_{ext,1}$, $C_{ext,2}$, R_1 and R_2) components.

Figure 2. (a) $|\Delta T|_{app}$ map carried out at $\Delta f = 1013$ Hz and $f = 440$ MHz. (b) $|\Delta T|_{app}$ map performed at $\Delta f = 113$ Hz and $f = 2$ GHz. (c) ϕ_T map performed at $\Delta f = 113$ Hz and $f = 2$ GHz. (d) Main paths taken by i_{in} at $f = 2$ GHz indicated in an amplifier's small-signal equivalent circuit pointing out the path provided by substrate capacitive coupling or Path A (solid blue line), and that expected without coupling or Path B (dashed red line).

Figure 3. ϕ_{τ} map (at $f = 2 \text{ GHz}$ and $\Delta f = 113 \text{ Hz}$) superposed to physical layout (a), correlating IC devices and components location with heat sources, and also indicating the direction of performed lateral profiles $\phi_{\tau}|_{M_2}$ and $\phi_{\tau}|_{L_{in}}$. $\phi_{\tau}|_{M_2}$ and $\phi_{\tau}|_{L_{in}}$ profiles are presented in (b) and (c) respectively, pointing out the location of heat sources detected by ϕ_{τ} measurements, IC area with noisy ϕ_{τ} readings (highlighted in grey), and performed average (in black), jointly with the fitted linear expression with x to extract the slopes α_1 , α_2 (in red), and α'_D (in blue).

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