

On-chip Radiometer with Miniaturized Near-field Antenna for Internal Body Thermometry

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Abstract—An on-chip correlation-Dicke hybrid radiometer for internal body thermometry at a frequency of 1.4 GHz is presented. The 3.8 mm by 2.3 mm GaAs MMIC includes two 90° hybrid couplers, a single-stage LNA in each path, and a switch. The hybrid coupler employs lumped elements instead of transmission lines to reduce chip size. Two single-stage LNAs are between the hybrid couplers to enhance robustness against input impedance mismatch. The circuit shows a gain of 13.4 dB, isolation of 16 dB, and a noise figure of 1.31 dB. Following the switch, an off-the-shelf band-pass filter, an on-chip LNA, and a detector are connected to provide a dc output proportional to the temperature at the antenna port. A 3.5 cm diameter circular near-field antenna is designed, capturing thermal noise from the liquid inside a human mouth. The dc voltage at the output is used to compute the temperature detected by the near-field antenna. *In-vivo* measurements are conducted using orange juice inside the human cheek, showcasing the ability to non-invasively track internal temperature.

Index Terms—GaAs monolithic microwave integrated circuit (MMIC), low noise amplifier (LNA), microwave thermometry, radiometer, RF switch, thermal noise

I. INTRODUCTION

The investigation of noninvasive internal body thermometry has been prompted by many benefits associated with the knowledge of internal body temperature. Existing methods include high-cost and non-wearable MRI, ingestible wireless pills, and heat flux devices with sub-cm penetration depth. Microwave radiometry is a non-invasive solution for estimating the temperature of a layer in a tissue stack, as described in [1]. A near-field antenna placed on the skin captures black-body noise power emitted by the tissue layers. By calibrating the received power against a noise source, the temperature of the tissues can be calculated. The information on the thickness and the electric characteristics of each layer is used to estimate the temperature of a specific layer. Operating in the 1.4–1.427 GHz band, the radiometer is useful for biomedical applications requiring interference mitigation because it is a quiet band assigned to radioastronomy.

Fig. 1 is a block diagram of a hybrid Dicke-correlation radiometer, designed to enhance robustness to input load variations and reduce sensitivity to gain fluctuations [2]. The architecture comprises a 3-dB coupler, two low noise

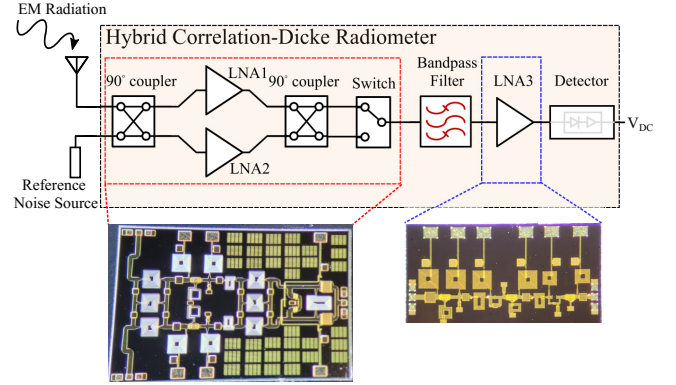


Fig. 1: Block diagram of the correlation-Dicke hybrid radiometer for internal tissue thermometry.

amplifiers (LNAs), another 3-dB coupler, and a Dicke switch. The system's noise figure (NF) is primarily determined by the coupler insertion loss and the NF of the LNAs. The radiometer bandwidth is limited by the bandpass filter with a bandwidth of 45 MHz. This corresponds to input thermal powers on the order of -100 dBm at room temperature [3]. A typical diode detector has a responsivity of a few V/mW. Therefore, about 45 dB of RF gain is needed to reach μ V-level voltage values after the detector, which is measurable using low-frequency instrumentation. Previous works have achieved these gain levels using multiple cascaded off-the-shelf LNAs [4] and a 3-stage LNA after a Dicke switch [5]. In this work, we achieve this gain level using two MMIC chips.

II. HYBRID RADIOMETER DESIGN

In a hybrid radiometer, there is a coupler positioned at the front with two LNA paths, similar to a correlation radiometer. After the second coupler, a switch alternates between two inputs, a near-field antenna and a reference noise source. Fig. 2 illustrates the circuit schematic and the layout of the 90° hybrid coupler. In lower microwave frequencies, transmission line branch couplers need a long $\lambda/4$ lines. However, couplers can be designed using lumped elements as an alternative to reduce size [6]. Following the first coupler, a single-stage common-source LNA with a degenerative inductor is implemented, followed by the same lumped element coupler. Subsequent to the second coupler, a single-pole double-throw

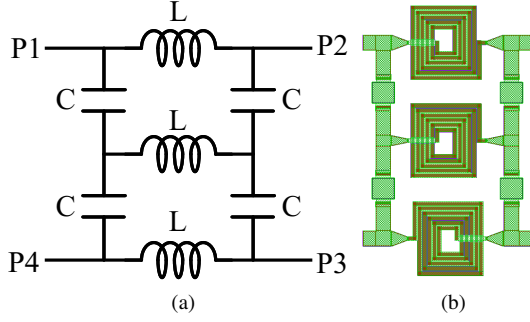


Fig. 2: (a) Schematic of lumped-element on-chip hybrid coupler (b) Layout of hybrid coupler.

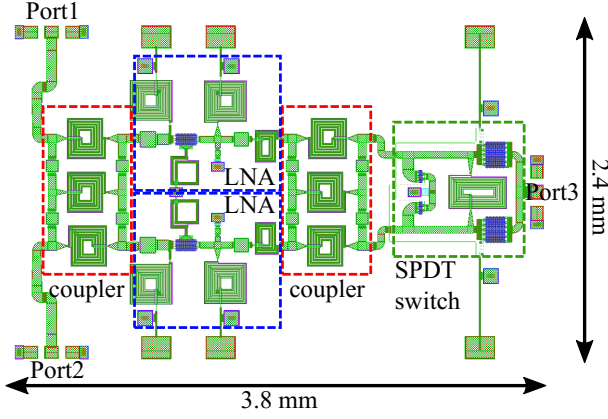


Fig. 3: Layout of the hybrid radiometer with two hybrid couplers, an LNA, and a SPDT switch.

(SPDT) switch is placed. This switch uses a series-shunt topology with the parasitic resonating inductor to improve insertion loss and isolation [7].

Fig. 3 illustrates the layout of the two hybrid couplers, side-by-side LNAs, and a switch fabricated using the 0.1- μm WIN Semiconductors enhancement-mode pHEMT GaAs process. The size of the MMIC die is 3.8 mm $\times$ 2.4 mm, with measured and simulated performance shown in Fig. 4. The peak gain is 13.44 dB at 1.4 GHz. The measured $|S_{11}| < -10$ dB for 0.7-1.73 GHz, and $|S_{22}| < -10$ dB for dc-1.63 GHz. The minimum measured NF is 1.31 dB at 1.36 GHz and NF=1.41 dB at 1.4 GHz. The measurement of the NF is approximately 0.19 dB higher than the simulation results.

A narrowband bandpass filter, LNA with ~ 35 dB of gain [8], and detector [3] complete the radiometer. The measured voltage responsivity of the whole system is shown in Fig. 5, with a peak at 1.405 GHz of 95 V/nW. The integrated value R is 4.28×10^9 V/nW. The power spectral density, p , of thermal radiation can be approximated as white noise in the microwave frequency range $p = kT$, so $\Delta V = k\Delta TR$, where R is the integrated responsivity. Using this equation, we can calculate $\Delta V/\Delta T = 59 \mu\text{V/K}$, meaning that the dc voltage increases by 59 μV when the temperature at the receiving element increases by 1 K.

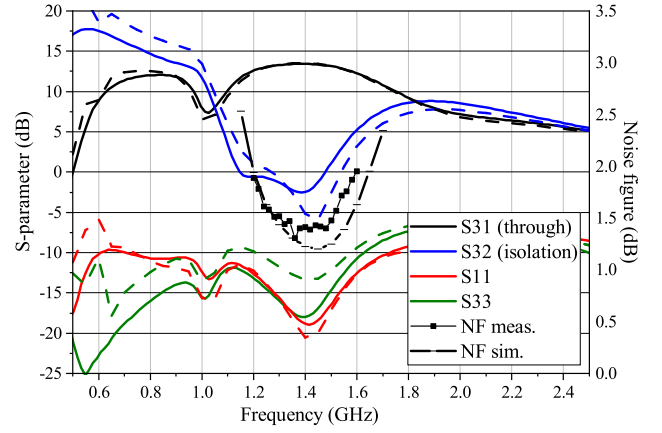


Fig. 4: Measured (solid line) and simulation (dashed line) S-parameter and noise figure of an MMIC hybrid radiometer.

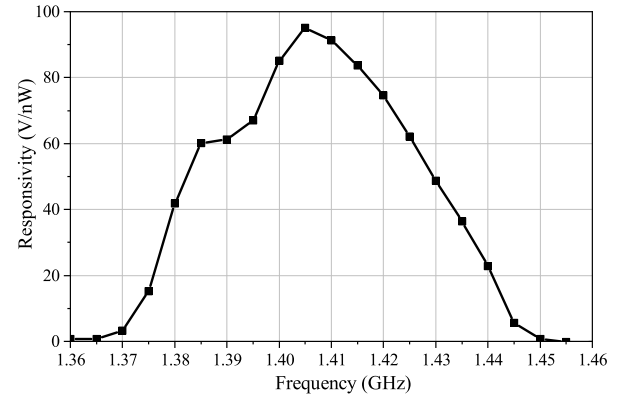


Fig. 5: Responsivity (V_{out}/P_{in}) of the radiometer, needed for temperature measurements.

III. NEAR-FIELD ANTENNA DESIGN

To receive black-body radiation from a subcutaneous tissue layer, a near-field antenna different from a free-space radiator is designed. The goals for the design include a small size for wearability, combined with spatial resolution in the lateral dimension and sensing depth in the vertical direction (Fig. 6). A circular patch with slot is chosen to reduce size and because the ground plane reduces back lobes that can receive interference. The goal, in this case, is to receive as much power as possible from the liquid layer under the skin, fat, and muscle layers of the cheek. The electrical properties of the tissue layers are found in [9] and the properties of liquids are found in [10].

Reciprocity is used to find the contribution of each tissue layer on the total received thermal noise power. Fig. 7(a) shows the reflection-coefficient magnitude of the near-field antenna when placed on the cheek. Fig. 7(b) illustrates the simulated Joule loss volume density of the near-field antenna and cheek tissue stack simulated in transmission with 1 W of input power at the antenna feed. The weights of each layer, which are used to estimate the internal temperature, are found as the ratio of the Joule loss in a particular volume to the total Joule loss.

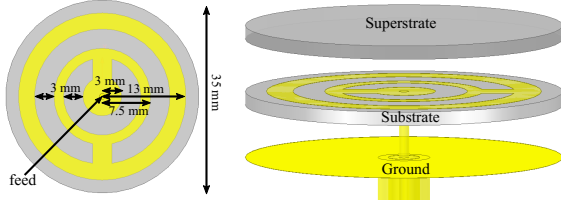


Fig. 6: Top view and cross-section of the near-field antenna designed for thermal power retrieval. 1.27 mm thick Rogers 3010 ($\epsilon_r=10.2$) used as substrate and superstrate.

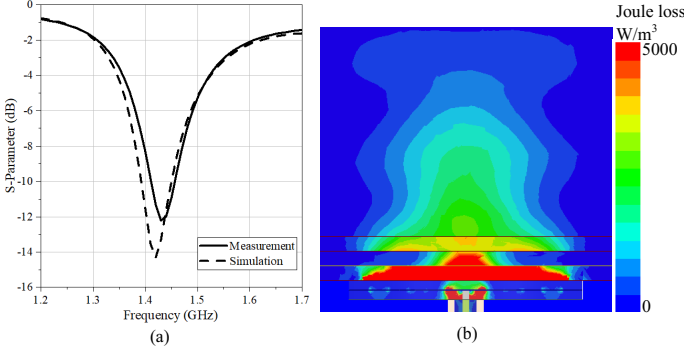


Fig. 7: (a) Reflection coefficient of near-field antenna when placed on cheek, skin phantom, and air. (b) Simulated Joule loss density of antenna on tissue stack of the cheek used to calculate the weights for temperature estimation.

IV. TEMPERATURE MEASUREMENTS

In-vivo measurements are done using temperature-varying liquid inside the mouth. The near-field antenna is placed on the cheek, Fig. 8, and a thermocouple placed inside the mouth provides ground-truth temperature of the liquid. Two other thermocouples are placed on the skin next to the antenna to monitor any skin/antenna temperature changes. Room-temperature liquid in the mouth is alternated with hot liquid. The radiometer tracks the temperature change of the liquid.

Weighting functions calculated from full-wave simulations [1] are used to estimate the temperature of the liquid:

$$T_{total} = \sum_{i=1}^N W_i \cdot T_i, \quad (1)$$

where the near-field antenna is placed on a tissue stack of skin, fat, muscle, and liquid. The calculated weighting factor of the skin is $W_{skin} = 46\%$, and the estimated temperature results of these measurements are shown in Fig. 9. The radiometer estimation follows the real-time thermocouple temperature measurement of the water with an average error of 0.72°C and maximum error of 2.5°C .

In summary, this paper presents a GaAs MMIC for a hybrid correlation-Dicke radiometer and demonstrates its ability to track temperature inside a human cheek from a near-field antenna placed externally on the skin.

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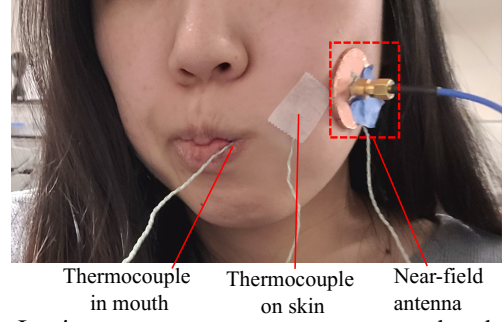


Fig. 8: *In-vivo* temperature measurement on the cheek with liquid in the mouth. The temperature of the liquid, skin, and antenna is measured independently with thermocouples.

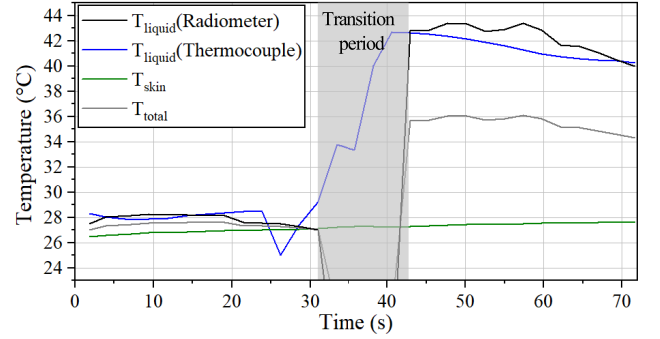


Fig. 9: Measured temperature of liquid using radiometer output. The temperature is compared with the real-time temperature measured with a thermocouple inside the mouth.

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