### Compact Microwave System for Quantitative Imaging: Preliminary Experimental Results

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Abstract—A new prototype of compact tomographic system for microwave imaging is presented in this letter. The target under test is surrounded by an ad-hoc 3D-printed structure, which supports sixteen custom antenna elements. Transmission measurements between each pair of antennas are acquired through a vector network analyzer connected to a modular switching matrix. The collected data are inverted by a hybrid nonlinear procedure combining qualitative and quantitative reconstruction algorithms. Preliminary experimental results, showing the capabilities of the developed system, are reported.

Index Terms—Microwave imaging; Tomography; Inverse problems

I. INTRODUCTION

In the last years there has been a growing interest in the development of compact, cheap, and portable microwave imaging systems in various applicative fields, and in particular for biomedical imaging [1]–[6]. In fact, microwaves have the potential ability of penetrating into dielectric materials, allowing to directly obtain information about the internal dielectric properties of the samples under test (SUT). Despite the potential advantages, there are still some problems to be faced, which motivate the ever expanding research activities on this topic. First, in many cases the targets are composed by inhomogeneous, lossy, and dispersive media (e.g., when dealing with biological materials). The electromagnetic waves are thus typically subject to high attenuations during the propagation through the target and the information about the material properties are contained in a complex way in the scattered field. Moreover, the dielectric contrast with respect to the external embedding may be high, requiring the adoption of matching layers. Consequently, it is necessary to properly design the antennas, the embedding structures, and the transmission/measurement hardware. Furthermore, appropriate inversion procedures, able to exploit the available a-priori information about the target, should be designed in order to process the measurements made available by the hardware.

In this letter, a new prototype of compact microwave imaging system is presented. It allows collecting frequency-stepped scattered-field data in a tomographic configuration by using a multi-static setup. The antennas have been specifically designed in order to minimize the reflections from the external surface and to optimize the propagation inside the target. An ad-hoc 3D printed holding structure is used to keep the radiating elements in contact with the target. The measured data are inverted by using a hybrid inverse-scattering procedure [7], which combines a delay-and-sum (DAS) qualitative algorithm [8] (providing a qualitative image of the dielectric discontinuities) with a quantitative method based on an inexact-Newton/Landweber (INLW) scheme [9] (providing a reconstruction of the distribution of the dielectric properties of the target). In particular, the obtained qualitative image allows to focus the INLW method on the regions of the target in which discontinuities with respect to the background are found. The capabilities of the developed system are assessed by means of preliminary experimental results.

II. SYSTEM DESCRIPTION

A block diagram of the developed prototype is shown in Fig. 1. It is composed by a vector network analyzer (VNA), a RF switch matrix connected to a set of ad-hoc antennas \( M = 16 \) antennas are adopted in the current prototype), and a control board used to drive the switches. The whole system is managed by a personal computer (PC), which is used to select the active antenna pair (via USB connection), control the VNA, collect the measurements (via Ethernet connection), and execute the reconstruction algorithms. The PC also takes care of the synchronization between the various components of the system.

![Fig. 1. Block diagram of the system architecture.](image-url)
The RF switch matrix is composed by two levels, as shown in Fig. 2. The first one, which is directly connected to the transmit and receive ports of the VNA, is composed by two 1:4 switch boards, whereas the second one is composed by four 2:4 switch boards, whose outputs are connected to the 16 antennas. For both levels, Peregrine Semiconductor’s PE42441 SP4T absorptive RF switches have been used in the switch boards. The working frequency band of such components ranges from 10 MHz up to 8 GHz. Each board has been manufactured by using a Rogers RO4350B substrate (characterized by complex relative dielectric permittivity \( \varepsilon_r = 3.66 - j0.0111 \) at 2.5 GHz) in order to reduce the RF signal attenuation and the changes in the electrical parameters. The switching subsystem allows to independently select a pair of antennas among the possible 240 combinations. One antenna at a time is used in transmit mode (i.e., it is connected to the TX port of the VNA), whereas the remaining ones are sequentially connected to the receiving port of the VNA for measuring the field scattered by the target. In order to reduce the interferences in the measurement, all the inactive antennas are terminated by using absorptive RF switch components. The switch control board is equipped with an ATmega328 microcontroller programmed to transparently pass the USB data to an I2C bus, which is connected to four 16 bit PCF8575DBE4 I/O expanders used to drive the RF switches.

Folded quasi self-complementary antennas (FQSCA) [10] have been used in the prototype (a schematic representation is shown in the inset in Fig. 1). Such antennas have been specifically designed in order to work in direct contact with the SUT, by reducing the reflections due to the mismatch with the target interface and optimizing the radiation inside the inspected structure. The operating bandwidth of the antennas ranges from 1.5 GHz up to 6 GHz. The radiating elements are kept in contact with the SUT by using a custom 3D printed circular holding structure (shown in Fig. 1) made of plastic with relative dielectric permittivity \( \varepsilon_r = 2.97 - j0.0595 \) (at 2.45 GHz). The separation between two adjacent antennas is 22.5° and the radius is 60 mm. In order to compensate different paths of the signal in function of the selected antenna pairs, a calibration is performed by subtracting a through measurement from each antenna combination.

The scattered-field data collected by the system are processed by using a hybrid qualitative-quantitative inversion scheme [7]. A flow chart of the developed inversion procedure is shown in Fig. 3. Starting from the measured stepped-frequency data, an initial qualitative reconstruction \( \Lambda(r), r \in \mathcal{D} \) (being \( \mathcal{D} \) the inspected area), is obtained by using a multistatic DAS method [8]. The time-domain response is synthesized by applying an inverse fast Fourier transform to the data. Such image provides a rough indication of the eventually present inclusions. Subsequently, a frequency-hopping (FH) inexact-Newton/Landweber method is used to obtain the quantitative distribution of the dielectric properties. In particular, for each considered frequency (in the following, the superscript \( f \) denotes the frequency index), the INLW method [9] is used to invert the non-linear and ill-posed scattering equation relating the unknown contrast function \( \chi^f = \varepsilon_r^f - \varepsilon_r^b \) (\( \varepsilon_r^f \) and \( \varepsilon_r^b \) being the complex relative dielectric permittivity of SUT and background, respectively) with the z-component of the scattered electric field \( e_z^f \), i.e.,

\[
e_z^f(r) = G_d^f(r)\chi^f(1 - G_d^f(r))^{-1}e_b^f(r) = F^f(\chi^f)(r)
\]

where \( e_b^f \) is the z-component of the electric field due to the background and \( G_d^f(r) \) are linear integral operators whose kernel is the Green’s function for the background. In order to exploit the information obtained in the qualitative step, the iterative update of the solution in the Newton scheme has been modified by multiplying the solution of the linearized problem by the value of the normalized qualitative map \( \Lambda \) (Fig. 3). As a result, since \( \Lambda(r) \in [0,1], \forall r \in \mathcal{D} \), the contrast function \( \chi \) is updated faster in the regions in which the qualitative method found relevant discontinuities with respect to the background.

III. PRELIMINARY EXPERIMENTAL RESULTS

The proposed system has been preliminarily tested by using a Plexiglas circular cylinder with diameter \( d = 120 \) mm (Fig. 4(a)) filled by a mixture of oil, water, and salt (relative dielectric permittivity \( \varepsilon_r \approx 3 - j0.73 \) at 2.45 GHz). The liquid mixture occupies a vertical depth of 90 mm. The investigation domain \( \mathcal{D} \) is a circular region of diameter \( d \) enclosing the outer cylinder, discretized into 1240 square subdomains with 3.12 mm side. Three plastic tubes of diameter \( d_i = 5 \) mm, filled with a different mixture of the same components (relative dielectric permittivity \( \varepsilon_r \approx 35 - j10 \) in the considered frequency band), are located at positions \( r_1 = (-20, -20) \) mm, \( r_2 = (20, -20) \) mm, and \( r_3 = (20, 20) \) mm.

Fig. 3. Flow chart of the inversion algorithm.
The electric field has been acquired for all the possible antenna pairs by considering 585 frequency steps in the range between 1 and 5 GHz. The acquisition time is mainly affected by the VNA measurement sweep time; switch setting and I/O expander latency can be neglected. For the presented results, a sweep time of 1 s has been set for each antennas combination, resulting in a total measurement time of 240 s.

The measured $S_{21}$ (magnitude) with and without the considered inclusions are shown in Fig. 4(b) for a pair of opposite antennas (antennas #6 and #14). Most of the scattering contributions are located between 2 and 4 GHz. Consequently, the FH-INLW method has been applied by considering $F = 13$ equally-spaced frequencies in this range. The maximum number of inner and outer iterations in each INLW inversion step are $N_{IN} = 100$ and $N_{NW} = 100$, and the loops are stopped when the variation in the residual falls below 1%. The results provided by the developed procedure are shown in Fig. 4(c)-(e). In particular, the obtained qualitative map, showing the presence of the three inclusions, is reported in Fig. 4(c). The quantitative reconstruction results at the final frequency step are shown in Fig. 4(d)-(e). As can be seen, the targets are accurately localized and the dielectric properties are quite correctly estimated.

IV. CONCLUSIONS

A compact microwave system for quantitative tomographic imaging has been presented in this letter. The system is composed by a set of ad-hoc antennas held in contact with the SUT by a custom 3D-printed structure, a modular switch matrix, a VNA, and a computer-based control and processing section. A hybrid qualitative/quantitative inversion method has been developed for processing the measured scattered field data. The effectiveness of the imaging setup has been assessed by means of preliminary experimental results. Future developments will be aimed at performing a wider experimental validation campaign with more complex targets.

REFERENCES