Hybrid Microwave Approach for Phaseless Imaging of Dielectric Targets
Sandra Costanzo, Senior Member, IEEE, Giuseppe Di Massa, Senior Member, IEEE,
Matteo Pastorino, Fellow, IEEE, and Andrea Randazzo, Member, IEEE

Abstract—A hybrid approach for phaseless imaging of dielectric targets is proposed in this letter. A two-probe measurement strategy with the related phase-retrieval method is adopted in conjunction with an inversion procedure based on an inexact-Newton method to give an efficient and low-cost imaging setup, avoiding the need of multiple acquisition surfaces. A preliminary experimental validation on real input data is presented.

Index Terms—Imaging, inverse scattering, microwaves, phase retrieval.

I. INTRODUCTION

In the last years, there has been a significant interest in developing microwave techniques to inspect dielectric targets. Nowadays, efficient inversion methods and prototypes of imaging systems are available in order to derive the dielectric parameters of a target under test starting from the measurements of the scattered field when the object is illuminated by incident waves. Different strategies have been proposed, whose validity is strongly related to the specific application [1]–[3]. Among these methods, a regularization approach based on the applications of an iterative algorithm built upon an inexact-Newton method (INM) has been developed in [4].

While, for certain applications (e.g., in medical imaging), the complexity of the illumination/measurement apparatuses can be relatively irrelevant, in other cases, the reduction of costs (and, consequently, of the system complexity) may be quite mandatory. In this light, phaseless imaging has been considered in some recent works [5]–[7]. For example, in [6], the required information about the region under test (e.g., its dielectric properties) is obtained from phaseless measurements of the total field by adopting a two-step procedure: The complex scattered field is first estimated, and subsequently, the inverse scattering problem is solved by using the retrieved data. In particular, to solve the phase-retrieval problem arising in the first step, a formulation in terms of squared cost functional is adopted, which, however, does not guarantee a unique solution when using a single measurement surface [6]. Therefore, the authors in [6] discussed the possible strategies to achieve a “convexification” of the original formulation, by adopting a proper starting guess and/or exploiting “a priori” information of the primary source, or using two sets of independent measurements. In this last case, it is highlighted by the same authors that the two scanning surfaces should be sufficiently spaced in terms of wavelength and their distance must be known with wavelength accuracy. In another work [7], a one-step imaging strategy based on the knowledge of amplitude-only total field data is introduced, but in order to guarantee the effectiveness of the solution, an accurate starting guess is required together with a suitable weighting of the cost functional.

In the present letter, we explore the combination of a two-probe approach for phase retrieval [8], [9] and an inversion method based on the INM [4], which exhibit very good regularization properties. A two-step procedure as adopted in [6] is considered but taking full advantage of the phase-retrieval method outlined in [8] and [9], which properly guarantees the attainment of the solution by avoiding the adoption of two different scanning surfaces, and proposing the use of two probes which simultaneously scan a single measurement region. In this way, a fast and efficient low-cost setup is obtained, with a reduced amount of required phaseless data.

This letter is organized as follows. In Section II, the proposed hybrid approach is described, whereas the combined method is experimentally tested in Section III. In particular, measured scattering data obtained by using the imaging facility at the Microwave Laboratory of the University of Calabria, Rende, Italy, are used.

II. HYBRID IMAGING APPROACH

The considered imaging configuration is sketched in Fig. 1. An unknown target, which is supposedly of cylindrical shape, is located in a known investigation area $D_{\text{inv}}$. A transmitting (TX) antenna illuminates the target with a transverse magnetic electromagnetic field. An $e^{j\omega t}$ time dependence is assumed. The scattered field is collected in a predefined set of points (the observation domain $D_{\text{obs}}$) by means of a receiving (RX) antenna. Both antennas can move around the target in order to collect multi-illumination multiview data.

The hybrid procedure proposed in this letter for phaseless microwave imaging is based on the adoption of the INM inversion technique but applied to scattered data as derived from amplitude-only measurements that are processed by the phase-retrieval technique described in [8] and [9]. For each
position of the TX antenna, it is assumed to scan the observation domain with two identical probes simultaneously moving along the measurement path (Fig. 1). They interfere each other by a simple microstrip circuit, as described in [8] and [9], thus providing phaseless near-field data which are subsequently processed to obtain the phase shift for each couple of measurement points, as expressed by the following formula [8], [9]:

$$\Delta \varphi = t g^{-1} \left[ \frac{|V_1 + j V_2|^2 - |V_1|^2 - |V_2|^2}{|V_1 + V_2|^2 - |V_1|^2 - |V_2|^2} \right]$$  

(1)

where $V_1 = |V_1|e^{j \varphi_1}$ and $V_2 = |V_2|e^{j \varphi_2}$ are the complex signals at the output of probes 1 and 2, respectively (Fig. 1) and $\Delta \varphi = \varphi_1 - \varphi_2$. A distance $d = i \lambda_0/2$, $i \geq 1$ between the probes is fixed as the minimum one imposed by the physical dimensions of the probes and able to guarantee, at the same time, a negligible mutual coupling between them.

The application of the interferometric formula (1) provides a number $i$ sets of complex near-field values, determined apart from a set of unknown phase shifts between samples, namely,

$$E(m) = \tilde{E}(m)e^{j \Delta \varphi(m)}$$  

(2)

where $\tilde{E}(m)$ denotes the known field quantities and $m$ describes the $i$ sets of measurement points as obtained from the successive positioning of the two probes (Fig. 1). In order to reconstruct the complex scattered field $\tilde{E}(m)$ from phaseless data, the unknown phase shifts $\Delta \varphi(m)$ are retrieved by adopting a nonredundant representation [9] for the set of all fields that the object under test can scatter. A suitable minimization procedure is then applied to find the solution as the intersection, in terms of greatest lower bound, between the set of all reduced fields that can be scattered by the source and the set of all scattered fields compatible with the measured data. Complete details of the adopted minimization algorithm can be found in [9].

After applying the phase-retrieval procedure for obtaining the values of the $z$-component of the scattered electric field $E_{\text{scatt}}$ in the measurement points, the inversion approach based on the INM is used to reconstruct the dielectric features of the target under test. In particular, the INM solves in a regularized sense the following equation, relating the scattered field data and the dielectric function $\epsilon(r) = \epsilon_r(r) - 1$ (with $\epsilon_r$ being the unknown space-dependent relative dielectric permittivity of the test region):

$$E_{\text{scatt}}(r) = \mathcal{M}(\epsilon) = G_0(c$I - G_0c)^{-1}E_{\text{inc}}(r)$$  

(3)

where $G_0/c$ at point $c_k$, and find a regularized solution $h_k$ to the linearized problem by using a truncated Landweber algorithm [4] (the number of inner iterations is denoted as $N_{\text{inv}}$).

3) Update the solution with $c_{k+1} = c_k + h_k$, and repeat until a maximum number of iterations $N_{\text{inv}}$ is reached or a predefined stopping rule is satisfied.

III. EXPERIMENTAL RESULTS

The proposed hybrid imaging procedure is experimentally validated by adopting the two-probe measurement strategy described in Section II. With reference to the imaging
configuration in Fig. 1, the TX antennas are positioned uniquely on three sides of the investigation domain, by assuming a total number $S = 9$ of TX positions, three for each side, namely, one at the center and the other two at distance $d_{TX} = 9.75$ cm up and below the center. Moreover, only the data collected on the opposite side with respect to that containing the TX antennas are used for the inversion procedure. For each measurement line, a number $M = 53$ of measurement points are considered, with a constant distance $d_{RX} = 0.75$ cm between two adjacent measurement points. This gives an overall side $L_{obs} = 39$ cm for the measurement domain. The phaseless electric field is measured at a frequency $f = 10$ GHz by using a simple and inexpensive setup, in which just a scalar network analyzer with simple detector diodes can be adopted. A standard X-band horn is assumed as both TX and RX antennas.

The target is an almost lossless wood cylinder of length approximately equal to 60 cm ($\sim 20\lambda$ at 10 GHz) and square cross section of side equal to about 4 cm, which is centered at coordinates $(-9, 6.5)$ cm. A photograph of the measurement setup is shown in Fig. 2. The investigation area is a square domain of side equal to 15 cm, centered at coordinates $(-7.5, 7.5)$ cm, which is discretized in $63 \times 63$ subdomains and initialized with the dielectric distribution obtained by applying the backpropagation algorithm [10]. The inversion algorithm is applied with $N_{lw} = 5$ inner iterations and a maximum number of $N_{in} = 20$ outer steps. The outer loop is stopped when the quantity $\zeta_k = |r_{k-1} - r_k|/r_k$, with $r_k = \|E_{\text{PR,scatt}}^\text{M}(c_k)\|_2$ being the residual on the data at the $k$th iteration, falls below a fixed threshold $\zeta_{th} = 0.01$.

It is worth noting that, in the considered example, the investigation area is not centered with respect to the measurement square. Such choice is made in order to limit the size of the inspected area. However, the measurement setup is designed to deal with investigation areas larger than the one considered here, e.g., up to about $30$ cm $\times$ $30$ cm. Consequently, the lengths of the measurement lines are selected according to this maximum length (with a margin at the ends of length equal to about $4.5$ cm). Moreover, the distance between two adjacent locations of the RX antennas is selected in order to properly sample the scattered fields. Anyway, on the basis of the results obtained in other papers dealing with the full complex data case (see, for example, [4]), it is expected that the use of a different measurement setup (e.g., with a measurement line with length equal to about the side of the investigation area) will not lead to significant deterioration in the reconstruction capabilities of the INM approach.

An example of the measured data is shown in Fig. 3, which provides the plot of the field amplitude and a comparison between the actual and the retrieved field phase values. As can be seen, the phase-retrieval procedure integrated in the inversion procedure is able to correctly reconstruct the input data. Fig. 4 shows the corresponding reconstruction of the
distribution of the relative dielectric permittivity inside the investigation domain. In particular, Fig. 4(a) reports the result provided by the hybrid approach, whereas Fig. 4(b) depicts the reconstruction obtained by a standard INM applied to the full complex data. Horizontal and vertical cuts along two lines passing through the center of the target are also shown in Fig. 5(a) and (b). As can be observed, the developed approach is able to satisfactorily retrieve the target dielectric profile. Table I reports the mean relative reconstruction errors, defined as

\[ \xi_{\text{inv,bg,obj}} = \frac{1}{N_{\text{inv,bg,obj}}} \sum_{n \in \Pi_{\text{inv,bg,obj}}} \frac{c_n^\text{rec} - c_n}{c_n + 1} \]  

(4)

where \( c_n \) and \( c_n^\text{rec} \) are the actual and reconstructed values of the contrast function in the \( n \)th cell in which the investigation area is discretized. The subscripts inv, bg, and obj indicate that the error is computed on the whole domain, the background, and the object, respectively (\( \Pi_{\text{inv,bg,obj}} \) denotes the sets of \( N_{\text{inv,bg,obj}} \) indexes spanning the corresponding parts of the investigation area). As can be seen, the hybrid approach provides results comparable to the standard procedure with full data. Moreover, it is worth noting that, although the phase is reconstructed with good accuracy, the errors are higher since the considered problem requires the solution of a very ill-posed inverse problem. For completeness, the mean values of the reconstructed imaginary parts are equal to 0.12 and 0.11 for the complex and phaseless data, respectively, whereas the corresponding standard deviations are equal to 0.12 and 0.11. The time needed by the hybrid approach to perform the reconstruction is equal to 142 s on a computer equipped with an Intel Core i5 processor working at 2.30 GHz and with 4-GB RAM. In particular, 7 s is needed for the phase retrieval, and 135 s is for the data inversion. The standard INM algorithm with the full complex data requires 116 s. It is worth noting that the difference between the two computational times is mainly related to the fact that, for this particular case, the INM requires more iterations to reach the convergence when considering phaseless data.

### IV. Conclusion

Microwave imaging of cylindrical targets has been considered in this letter. A hybrid approach that is able to reconstruct the electromagnetic features of dielectric objects from the knowledge of amplitude-only scattered field data acquired on a single measurement surface has been proposed. In particular, a two-probe measurement strategy and the related phase-retrieval procedure have been combined with an inversion procedure based on an INM and tested against experimental data. Further work will be devoted at evaluating the capabilities and limitations of the combined strategy against targets having higher relative permittivity values as well as dispersive objects.

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### References


### Table I

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