Compressed Sensing Based Super-Resolution Layer Structure Analysis for Terahertz Time-domain Spectroscopic Imaging System

Hayatomomaru Morimoto[1] and Shouhei Kidera[1,2]
1.Graduate School of Informatics and Engineering, The University of Electro-Communications, Japan
2. Japan Society Science and Technology (JST), PRESTO, Japan.

***Abstract*—This paper introduces a super-resolution depth imaging method based on a compressed sensing scheme with reference signal optimization, particular for data obtained out of focus. The inherent problem in the conventional terahertz time-domain spectroscopic (THz-TDS) system is that the depth resolution is considerably degraded due to pulse dispersion at the out-of-focus area. To overcome the above issue, we introduce the compressed sensing (CS) based super-resolution depth imaging, with the appropriate reference signal model. The effectiveness of our method is validated through TDS-THz measured data from double layer structure object.**

I. INTRODUCTION

Terahertz (THz) imaging systems are promising for various high-resolution sensing applications such as non-destructive testing for industrial product or security screening of human body, and is also promising for medical imaging applications, such as e.g., skin cancer detection. Multi-layer structure analysis is one of the most important issue for the THz imaging applications, such as thickness estimation of thin film. On the contrary, the resolution of the depth direction is determined by the bandwidth of the THz pulse, and the super-resolution feature is strongly demanded using the state-of-the-art signal processing scheme. Some literature demonstrated that the compressed sensing (CS) based methods have achieved such super-resolution characteristic in radar signal processing field [1], or THz-band imaging scenario [2] [3]. However, it has been experimentally demonstrated that the bandwidth of the received signal becomes narrower in the case that the reflection layer is located out of the focal point of a dielectric lens, and the resolution of CS is also degraded due to the above signal deformation.

To address with the above problem, this paper investigates and validates the performance for the CS based super-resolution imaging where the optimal reference signal is varied according to the depth of layers. The experimental data obtained by the THz time-domain spectroscopy (THz-TDS) systems demonstrated that our approach remarkably enhances the resolution and accuracy for the depth imaging for the thin double layered object.

II. COMPRESSED SENSING BASED SIGNAL SEPARATION

Under the assumption that the depth profile of multi layered object, as $\boldsymbol{\theta}$, has a sparse distribution the following l_1 norm regularization scheme can be applied to solve the $\boldsymbol{\theta}$ as:

$$\hat{\boldsymbol{\theta}} = \underset{\boldsymbol{\theta}}{\arg\,\min}(||\boldsymbol{x} - \boldsymbol{A}\boldsymbol{\theta}||_2^2 + \lambda||\boldsymbol{\theta}||_1) \quad (1)$$

where $\boldsymbol{x}$ denotes the measured signal in the time-domain, $\boldsymbol{A}$ is the observation matrix composed of time-series response of the assumed reference signals, and λ denotes the regularization coefficient. $||*||_m$ denotes the l_m norm. In general, the reference signal can be given by the transmitted signal, because the pulse waveform from the source is invariant to the penetration depth. Then, this waveform mismatching incurs the non-negligible inaccuracy or lower resolution in depth imaging, in the CS or other filtering schemes. The above problem can be addressed by adaptive reference signal model according to the depth.

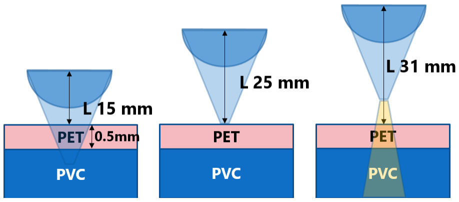
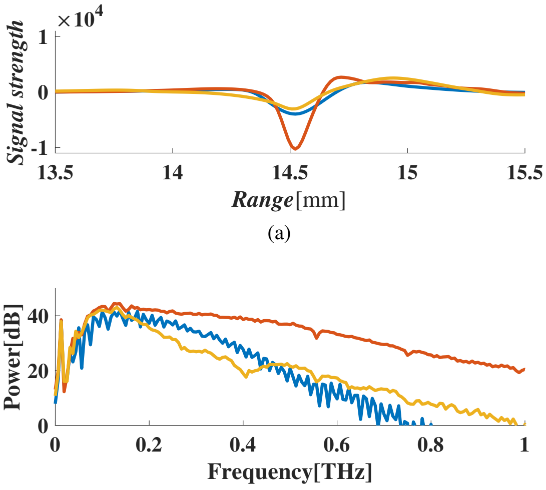


Fig 1. Observation model. Depths of PET surface are 15 mm, 25 mm, 31 mm, respectively.



(b)

Fig 2. Reference signals in varying the depths of PEC plates, which are 15 mm(blue), 25 mm(red), 31 mm(yellow), respectively . (a): Temporal responses after time shift compensation. (b): Power spectrum.

III. EXPERIMENTAL VALIDATION

A. Observation model

Figure **1** shows the observation models of the experiment, using the THz-TDS. The transmitted pulse has 0.131 THz center frequency and 0.121 THz bandwidth. The set of transmitting and receiving dielectric lens with 25 mm focal length is scaned on a plane, where the 70 observation points are equally sampled for 7.5 mm $\leqq x \leqq$ 24.5 mm. Surface thin dielectric medium

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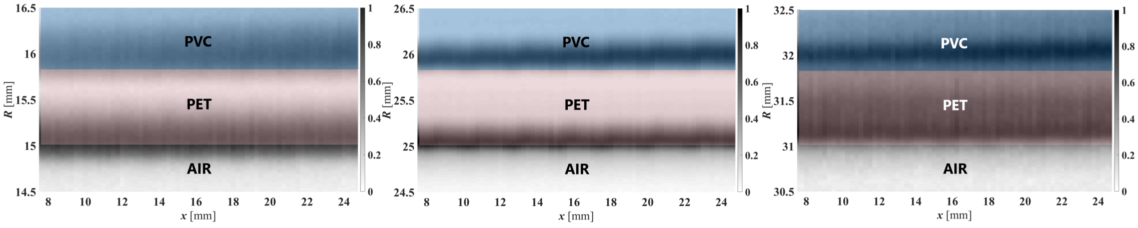
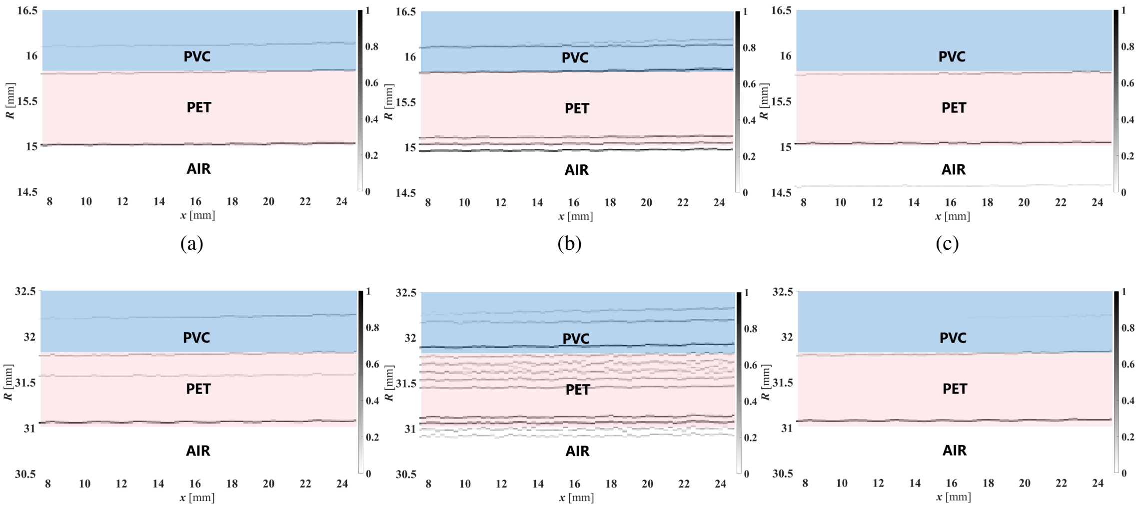


(a) (b) (c)

Fig 3. Raw data obtained by the THz-TDS system when the depth of PET surface is changed. (a): L15 (out-focus) , (b): L25 (on-focus), and (c) L31 (out-focus).



(a) (b) (c)

(d) (e) (f)

Fig 4. Depth image obtained by the CS algorithm, in varying the reference signal. (a)-(c) : Case for L15, and (d)-(f) : Case for L31. (a) and (d): Reference signal model with L15. (b) and (e): Reference signal model with L25. (c) and (f): Reference signal model with L31.

TABLE I: BandWidth and Distance Resolution of reference signals.

Case	L15	L25	L31
3dB bandwidth	0.148 THz	0.356 THz	0.121 THz
Depth resolution	0.203 mm	0.421 mm	0.124 mm

is lossy polyethylene terephthalate(PET) with 2.779 relative permittivity and 0.5mm thickness. The second dielectric layer is made of hard polyvinyl chloride(PVC).

B. *CS performance with each reference signal*

To validate and discuss the depth dependency for thickness estimation, we set the double layered target at the three different depths, 15mm, 25mm(focal depth), and 31 mm from the lens, the cases of which are named as L15, L25, and L31, respectively. We also prepare the three reference matrices as $\boldsymbol{A}^{\mathrm{L15}}$, $\boldsymbol{A}^{\mathrm{L25}}$, and $\boldsymbol{A}^{\mathrm{L31}}$, which are constituted of the reflection responses from a large PEC plane located at the depths at 15 mm, 25 mm, and 31 mm, respectively. Figure 2 shows the above reference signals. As shown in this figure, the reference signals in L15 and L31 considerably differs from that obtained L25 (on-focus) and their bandwidths becomes also narrower, which incurs a lower depth resolution as shown in Table I. Table I shows each bandwidth and depth resolution. Figure **3** show the received signals at L15, L25, and L31 cases, and show that in the case of L15 and L31, the clear separation between PET and PVC surfaces are hardly achieved due to lower depth resolution. On the other hand, Fig. **4** shows the output of the CS filter using each reference signal. , and demonstrated that the CS algorithm with suitable reference signal, namely, the same depth, accomplishes more accurate and super-resolution property, whilein the case using inappropriate reference signal, it also suffers from unnecessary responses due to waveform mismatching.

IV. CONCLUSION

This paper investigated the CS-based super resolution depth imaging issues, by focusing on the reference signal, an appropriate of which can be variant in terms of depth of reflection surface.

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