Study of subwavelength imaging from a single broadband antenna

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Abstract

Subwavelength imaging is a long sought-after goal in various imaging applications, which usually require an array of antennas or mechanical scanning. Here, we present the concept of single antenna for imaging with the aids of metamaterial lens and compressive sensing processing. We propose, design, and realize a spatial-temporal resonant metamaterial lens based on a planar array of closely spaced resonators, which provides the unique ability to produce real-time data when illuminated by broadband electromagnetic waves. A sparsity-promoted reconstruction algorithm is specially developed to process the data acquired by the single-antenna imaging system. We demonstrate experimentally that this novel imaging system, in combination with the advanced reconstruction algorithm, is capable of producing high-resolution images without using mechanical scanning or antenna arrays. We expect that the imaging methodology will make breakthroughs in high-resolution imaging in microwave, terahertz, optical, and ultrasound regimes.

1. Introduction

Conventionally, there are two types of popular active imaging systems: real-aperture (RA) system and synthetic-aperture (SA) system. A SA system relies on the mechanical movement of single radar to form virtually a large scanning aperture via post-processing, which is typically inefficient at data acquisition. On the contrary, a RA system, composed of a large number of antenna elements, has much more flexibility in the measurement modes, but such system sacrifices the size, weight, power, and price advantages of single radar system. Now, a natural question arises: is it hopeful to get a high-resolution image from a single radar? The answer is encouraging. The recent theory of compressive sensing (CS in short) has established that a reduced number of measurements allows us to get a high-resolution image by designing more clever measurement manner so chat each measurement gathers information from all parts of the objects in a controlled but pseudo-random fashion. In this study, we propose the concept of a single broadband radar for high-resolution imaging by exploring two recent advancements made in physics and mathematics: the spatio-temporal resonant lens [2] and compressive sensing [6, 7]. We design a spatial-temporal lens for controlling the interaction of broadband electromagnetic waves with probed objects in the pseudo-random manner. We demonstrate experimentally that such single radar system is capable of producing a high-resolution image without any mechanical movement and phase shifter, assistant with a developed sparsity-promoted reconstruction solver.

As a matter of fact, inspired by the spirit of CS, several recent compressive imagers have been invented [1, 3, 5, 7]. On practical grounds, these CS implementations require the sequential generation of a large number of random patterns, and thus remain inefficient in the sense of data acquisition. For instance, the single pixel camera uses a digital array of micromirrors to sequentially reflect different random portions of the object onto a single photodetector [3]. The metaimager performs sequential measurements of scene using a frequency-based encoding of the measurement modes [1]. Apart from these techniques, the advantageous of our imager is obvious because of the use of single radar in combined with broadband illumination, which removes completely the sequential measurements, and thus drastically fasten the data acquisition. Moreover, the proposed single radar imaging system amounts to using a spatio-temporal resonant lens to

978-1-4673-5225-3/14/$31.00 ©2014 IEEE

encode the spatial details of probed targets into temporal domain, which mathematically leads to a measurement matrix well matched to CS. In that sense, a spatio-temporal resonant lens can serves as an easy-implementation apparatus for compressive measurements for our purpose.

2. Methodology

Our approach and its implementation in microwave regime (from 8.5GHz to 12.5GHz) are summarized in Fig. 1. Here, a single broadband antenna (called master antenna for convenience) fixed at $\mathbf{r}_d$ is used to emit a narrow pulse, and receive echoes scattered from objects under investigation. A planar spatial-temporal resonant lens (called slaver antenna) is introduced, which transfers the temporal signal encoding the spatial information of probed objects into the master antenna. In order to mimic the pseudo-random measurement mechanism required by CS, such spatial-temporal resonant lens consists of 20×20 randomly oriented elements of frequency selective surface structure [2]. An element uses stacked micro-strip patches as the inner- and outer-surface radiators. We excite the lens with a small x-polarized dipole source located 150mm on top of the resonant lens. This source emits a Gaussian pulse with 5ns duration.

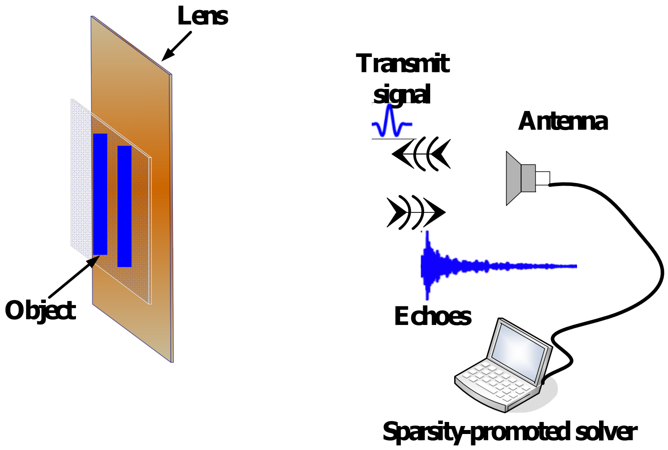
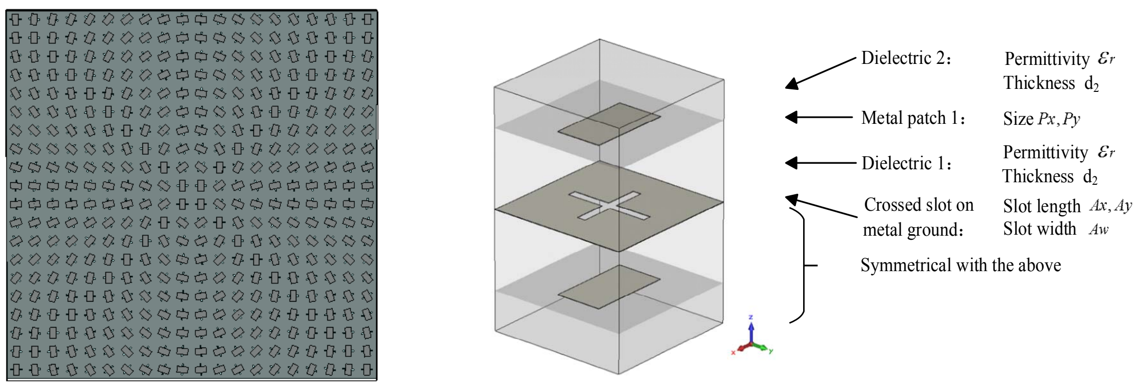


Fig. 1. Proposed Imaging setup



(a) (b)

Fig. 2. (a)Proposed spatio-temporal lens, and (b)the detail of a constitute unit ceil.

Here, we demonstrate that our single broadband radar system is capable of producing a high-resolution image lifting any mechanical movement and phase shifter. Without loss of generality, we assume that the imaged scene consists of Q discrete pixels. Mathematically, the echo received by the mater antenna at the angular frequency of ω

is

$$y(\omega) = \sum_{q=1,2,\ldots,Q} G^2(r_d, r_q; \omega) O(r_q) \tag{1}$$

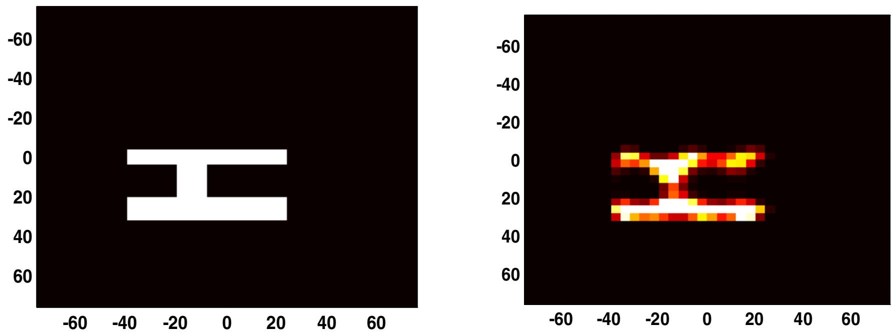
where $G(r_d, r_q; \omega)$ is the three-dimensional Green's function describing system formed by the spatial-temporal resonant lens. The square of Green's function in Eq. (1) accounts not only the forward wavefield from the master antenna through lens to objects, and but also the backward wavefield from objects through the slaver antenna to the master antenna. In Eq. (1), the assumption of Born approximation (or single scattering approximation) has been made, which holds for the weakly scattering objects. Generally, to solve Eq. (1) is challenging because it is strongly ill-posed due to severely inadequate measurements in relate to unknowns. Thanks to the elegant shift by CS, one can faithfully recover $O(r_q)$ by implementing a sparsity-promoted reconstruction algorithm [6, 7].

Table I. Details of spatio-temporal lens

Parameters	Values	Parameters	Values
A_x	6.46mm	P_y	4mm
A_y	7.34mm	d_1	1.5
A_w	0.75mm	d_2	0.35
P_x	7.14mm	ε_r	2.2

3. Results

As an illustrating example, we consider the capability of proposed single-antenna system imaging to image a simple structure, as shown in Fig. 3(a), with the relative parameters 4.7(see Fig. 3(a)) launched at foam bed supported by microwave absorbers.



(a) (b)

Figure 3. The ground truth to be imaged (a), and the reconstructed result by proposed single-antenna imaging system in combined with a sparse promoted solver. In these figures, the x-axis and y-axis denote the locations along x-direction and y-direction in mm.

The object consists of two dielectric bars with a refraction index of 1.5 and a square cross-section of 30nm. For this setup, we voluntarily opt for a low-refractive-index-contrast, which is typical of soft-matter objects. Note that all simulated data are generated by implementing the commercial software of CST Microwave Studio 2010. By applying the sparsity-promoted solver to Eq. (1), we arrive at the imaging results as shown in Fig 3(b). The image obtained in Fig.3b clearly shows that the two objects separated by distance of 100nm can be resolved from far-field, from which we estimate roughly our limiting resolution to about 9cm (about 0.3 times wavelength). Despite the simplicity of these imaged objects, those first results prove that the subwavelength information of an object, which is registered in the far-field region by the spatio-temporal resonant lens, can be restored by processing the temporal data acquired by a single antenna.

4. Conclusion

In summary, we develop the concept of single-antenna system for subwavelength imaging, which benefits from the use of spatial-temporal lens and sparse reconstruction. Furthermore, unlike most current compressive sensing hardware, this system gives access to many compressive measurements by one single antenna, drastically speeding up acquisition. Such system relies on the spatial-temporal lens, which encodes the spatial structures of probed object to the temporal domain. Furthermore, such lens serves as an efficient apparatus for compressive measurement, which shifts the complexity of devising CS hardware from the design, fabrication and electronic control to a simple and single calibration procedure. It is expected that such single-antenna concept also can find its application for subwavelength imaging, if using more specialized spatial-temporal lens and more efficient sparse reconstruction solver.

5. References

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