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Single-sensor Microwave Imager Using 1-bit Programmable Coding Metasurface

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Abstract

We present a computational single-sensor imager using 1-bit programmable coding metasurface for efficient microwave imaging. Unlike a conventional coded aperture imager where elements on random mask are manipulated in the pixel-wised manner, the controllable elements in the proposed scheme are encoded in a column-row-wised manner. As a consequence, this single-sensor imager has a reduced data-acquisition time with improved obtainable temporal and spatial resolutions. Besides, we demonstrate that the proposed computational single-shot imager has a theoretical guarantee on the successful recovery of a sparse or compressible object from its reduced measurements by solving a sparsity-regularized convex optimization problem, which is comparable to that by the conventional pixel-wise coded imaging system. The performance of the proposed imager is validated by both numerical simulations and experiments for microwave imaging.

1. Introduction

Microwave imaging is an important and powerful technique in science, engineering, and military. Over the past decade, the coded aperture imaging system in combination with the sparsity-regularized reconstruction algorithm has gained intensive attentions [1–3]. A coded aperture imaging architecture relies on the use of a sequence of random masks, through which the modulated information of the probed object was fully captured by a single fixed sensor. When the probed object allows for a low-dimensional representation in certain transformed domain, either pre-specified or trained, such as DCT, wavelet, etc., it is known that such a single-sensor imager benefits from a fundamental fact that the number of measurements could be drastically reduced compared to that required by conventional imaging techniques.An essential issue of the single-sensor imager is the construction of multiple- mode modulators or masks, which is not well tackled and remains challenging in designing the controllable masks, especially in the microwave frequencies. More recently, the programmable coding metasurfaces [4] have been introduced to dynamically manipulate the EM waves in both microwave frequency and beyond.

Here, we propose a new method to realize the large-aperture single-sensor microwave imager by utilizing the 1-bit programmable coding metasurface composed of an array of voltage-controllable particles. Each metasurface particle illuminated by the incident wave could be in a state of two distinct responses: “1” for important radiation when the loaded voltage is at a high level, and “0” for almost negligible radiation. In this way, a sequence of different quasi-random radiation patterns are easily generated by managing the applied voltages of the coding metasurface, which could provide adequate modes in our imaging system. Although the proposed imager is an instance of the coded aperture imaging systems, it is different from the conventional CS-inspired imagers (e.g., the single-pixel camera[1] and a recent terahertz single-sensor imager[2]) where the elements of the random masks are manipulated in the pixel-wised manner. The controllable elements in this scheme are manipulated in the column-row-wised manner, which could greatly simplify the shutter control mechanism of the pixel-wised coded exposure. We also show that the proposed large-aperture computational single-shot imager has a theoretical guarantee on successful recovery of a sparse or compressible object from its reduced measurements by solving a sparsity-regularized convex optimization problem. Furthermore, we fabricate a sample of such a 1-bit coding metasurface and conduct the proof-of-concept imaging experiments in the microwave frequencies, validating the performance of the novel single-sensor imaging system.

2. Methods

As illustrated in **Figure 1,** the proposed single- sensor imager is composed of three parts, including a transmitter working at single frequency to launch the incident wave, a 1-bit programmable coding metasurface to generate the sequentially CS random masks for modulating spatial wavefronts emanating from the transmitter, and a single sensor fixed at some distance away from the metasurface to collect the wave fields scattered from the probed object. The metasurface consists of a two-dimensional array of 1-bit voltage-controllable coding particles; and each particle could be in a state of two distinct responses: “1” when loaded with a high-level voltage for important secondary radiations, and “0” for almost negligible radiation. The coding elements in the proposed scheme are manipulated in the column-row-wised manner, rather than the pixel-wised manner in the conventional CS methods**.** Specifically, the coding metasurface with $N_x \times N_y$

particles is controlled by $N_x + N_y$ instead of $N_x \times N_y$ random binary sequences. In this way, the programmable coding metasurface is capable of producing quasi-random patterns in a very flexible and dynamic manner.

The metasurface with the mth coded pattern, illuminated by an x-polarized plane wave, as illustrated in **Figure 1**, produces approximately an x-polarized radiation field at the location $\boldsymbol{r}$:

$$E^{(m)}(\boldsymbol{r}) = \sum_{n_x=1}^{N_x}\sum_{n_y=1}^{N_y}\tilde{A}_{n_x,n_y}^{(m)}g(\boldsymbol{r},\boldsymbol{r}_{n_x,n_y}) \quad (1)$$
$$m = 1,2,\ldots,M$$

where $g\left(\boldsymbol{r},\boldsymbol{r}_{n_x,n_y}\right) = \frac{exp\left(jk_0\left|r-r_{n_x,n_y}\right|\right)}{4\pi\left|r-r_{n_x,n_y}\right|}$ is the three-dimensional Green's function in free space, k_0 is the operation wavenumber, M is the total number of the coded patterns, $\tilde{A}_{n_x,n_y}^{(m)} = A_{n_x,n_y}^{(m)}\exp\left(j\varphi_{n_x,n_y}^{(m)}\right)$ describes the induced x-polarized current with the amplitude $A_{n_x,n_y}^{(m)}$ and phase $\varphi_{n_x,n_y}^{(m)}$ on the $(n_x,n_y)th$ unit of the coding metasurface, and $\boldsymbol{r}_{n_x,n_y}$ is the coordinate of the $(n_x,n_y)th$ metasurface particle. In Equation (1), the double summation is performed over all pixels of the coding metasurface, where n_x and n_y denote the running indices of the particle of the coding metasurface along the x- and y-directions, respectively. The probed object with contrast function $O(\boldsymbol{r})$, falling into the investigation domain V, is illuminated by the wave field of Eq. (1), giving rise to the following electrical field at $\boldsymbol{r}_d$:[1–3]

$$E^{(m)}(\boldsymbol{r}_d) = \sum_{n_x=1}^{N_x}\sum_{n_y=1}^{N_y}\tilde{A}_{n_x,n_y}^{(m)}\int_V g(\boldsymbol{r},\boldsymbol{r}_{n_x,n_y})g(\boldsymbol{r}_d,\boldsymbol{r})O(\boldsymbol{r})d\boldsymbol{r} \quad (2)$$
$$m = 1,2,\ldots,M$$

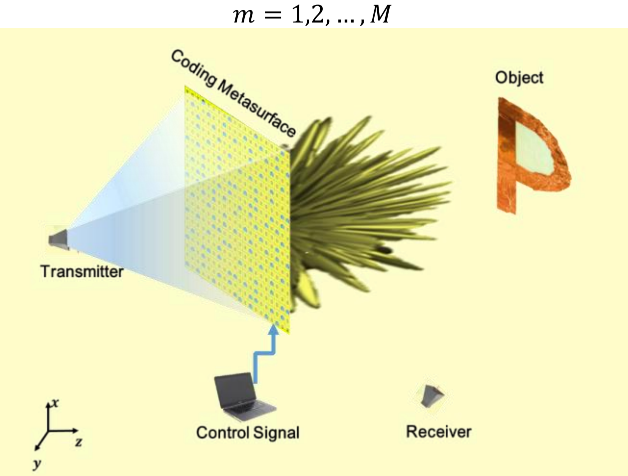

Figure 1. The schematic of the proposed single-sensor imager: this imager consists of a transmitter working with single frequency launches an illumination wave, a one-bit coding metasurface is responsible for generating sequentially random masks for modulating the spatial wavefront emerged from transmitter, and a single sensor is fixed at somewhere for collecting the wave field scattered from the probed object.

In the context of computational imaging, Equation (4) can be reformulated in the following compact form:

$$E^{(m)} = \langle\tilde{\boldsymbol{A}}^{(m)},\tilde{\boldsymbol{O}}\rangle \quad (6)$$
$$m = 1,2,\ldots,M$$

where the symbol $\langle\cdot\rangle$ denotes the matrix inner-product, the matrix $\tilde{\boldsymbol{A}}^{(m)}$ has the size of $N_x \times N_y$ with entries of $\tilde{A}_{n_x,n_y}^{(m)}$, and the matrix $\tilde{\boldsymbol{O}}$ with the size of $N_x \times N_y$ is populated by $\tilde{O}_{n_x,n_y}$. Equation (6) reveals that the resulting problem of the computational imaging consists of retrieving $N = N_x \times N_y$ unknowns $\{\tilde{O}_{n_x,n_y}\}$ from the M measurements $\{\boldsymbol{E}^{(m)}(\boldsymbol{r}_d)\}$. Typically, Equation (6) has no unique solution if $N > M$ due to its intrinsic ill-posedness. To overcome this difficulty, we pursue a sparsity-regularized solution to Equation (6) since we believe that the probed object $\tilde{\boldsymbol{O}}$ has a low-dimensional representation in certain transform domain denoted by $\boldsymbol{\Psi}$, i.e., $\boldsymbol{\Psi}(\tilde{\boldsymbol{O}})$ being sparse. Therefore, the solution to Equation (6) could be achieved by solving the following sparsity- regularized optimization problem:

$$min_{\boldsymbol{O}}\left[\frac{1}{2}\sum_{m=1}^{M}\left(E^{(m)} - \langle\tilde{\boldsymbol{A}}^{(m)},\tilde{\boldsymbol{O}}\rangle\right)^2 + \gamma||\boldsymbol{\Psi}(\tilde{\boldsymbol{O}})||_1\right] \quad (7)$$

where γ is a balancing factor to trade off the data fidelity and sparsity prior.

We now demonstrate that our single-sensor imager based on the 1-bit column-row-wised coding metasurface has a theoretical guarantee on successful recovery of a sparse or compressible object from its reduced measurements by solving a sparsity-regularized convex optimization problem. The conclusion is summarized in ***Theorem 1***.

Theorem 1. With M, N and S defined as previously, a S-sparse N-length signal can be accurately retrieved with the probability not less than $2\exp(-C(logSlogN)^2)$, provided that the number of measurements with $M \geq C * SlogN/S$ is up to a polynomial logarithm factor, where C is a constant depending only on S.

3. Results

A set of proof-of-concept experiments have been conducted to verify the performance of the proposed single-sensor microwave imager. To accomplish this goal, we fabricate a sample of 1-bit programmable metasurface that is encoded in the column-row-wised manner, as shown in **Figure 2a**. In our imaging experiments, a vector network analyzer (VNA, Agilent E5071C) is used to acquire the response data by measuring the transmission coefficients (S21). More specifically, a pair of horn antennas are connected to two ports of the VNA through two 4m-long 50-Ω coaxial cables: one is used for launching the incident wave, and the other for collecting the response data emanated from the probed object, illustrated in **Figure 2b**. To suppress the measurement noise level, the average number and filter bandwidth in VNA are set to 10 and 10 kHz, respectively. The experiments are carried out in a microwave anechoic chamber with the size of $2 \times 2 \times 2m^3$. Other relevant parameters are kept as the same as those adopted in the numerical simulations.

First, these experiments are conducted to show the ability of the proposed coding metasurface to generate the controllable radiation patterns. The biased voltages of the coding metasurface in both column and row distributions could be digitally controlled by toggling different triggers, which control the 'ON' and 'OFF' states of the biased PIN diodes, thereby the required '0' or '1' state of each metasurface particle could be realized. Therefore, different quasi-random radiation patterns could be achieved. Totally 1000 random radiation patterns are generated for the imaging purpose, and three of them are shown in **Figures 2d.** These radiation patterns are obtained by scanning the electrical fields at 3 mm away from the coding metasurface with a 50Ω-coaxial SMA tip, followed by the near-field-to-far-field transformation. The measured radiation patterns resemble those predicted by the numerical simulations, despite a little mismatches arising from the measurement errors, parasite effects of the diodes, and other possible reasons, which implies that the proposed 1-bit column-row-wise coding metasurface can be utilized to generate incoherent random-like masks.

Second, two sets of imaging results are presented to demonstrate the performance of the proposed single-sensor imager. As done in the numerical simulations, the "P" and "K"-shaped metallic objects are considered in the experiments, shown in **Figure 2c**. The reconstruction results for "P" ("K") are provided in **Figure 2e-g (Figure 5h-j)**, considering different numbers of measurement M= 200, 400, and 600, respectively. Similar conclusions to the previous numerical simulations can be drawn immediately. The experimental imaging results clearly validate the feasibility of the proposed single-sensor imaging system based on the 1-bit column-row-wised programmable coding metasurface.

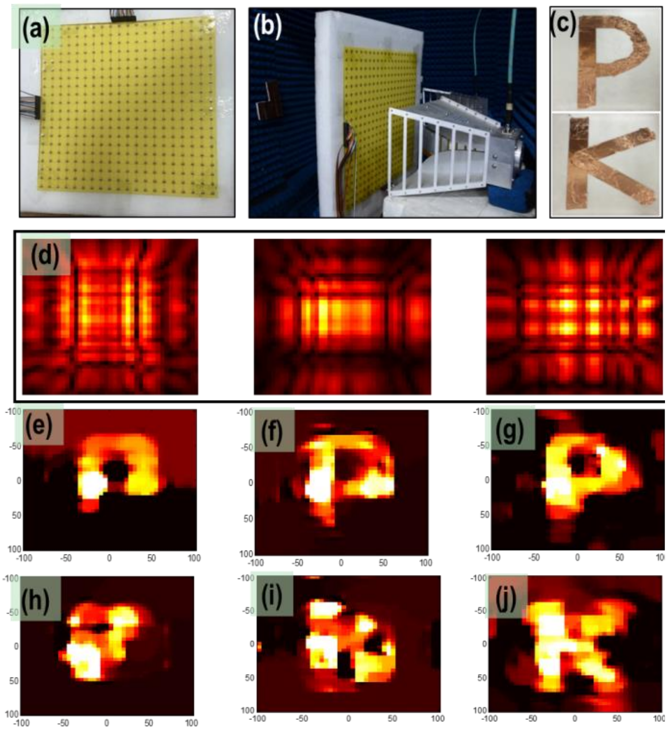

Figure 2. **(a)** The fabricated sample of the column-row-wise coding metasurface. (b) The experimental single-sensor imaging system based on the 1-bit programmable coding metasurface. (c) the "P"- and "K"-shaped metallic objects for imaging test. **(d)** Three samples of the radiation patterns of the coding metasurface. (**e-g**) The measured imaging results for the "P"-shaped metallic object with different measurement numbers M=200, 400, and 600, respectively. (**h-j**) The measured imaging results for the "K"-shaped metallic object with different measurement numbers M=200, 400, and 600, respectively.

4. Summary

In conclusion, we presented a new single-sensor imager based on the 1-bit column-row-wised programmable coding metasurface for the high-rate- frame electromagnetic imaging. A sample of such a 1-bit coding metasurface was fabricated and the proof-of-concept imaging tests were conducted in microwave frequencies to validate the single-sensor system for the high-frame-rate imaging. We also demonstrated that the very simple 1-bit column-row-wised coding metasurface has a theoretical guarantee to ensure that the required measurement number is comparable to that for the conventional pixel-wise encoded masks while maintaining nearly the same imaging quality. The new imaging system may be extended to the terahertz frequencies.

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