A single pixel Millimeter-wave imaging system based on metamaterials

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***Abstract*—Based on metamaterials and compressive sensing theory, we designed a single pixel millimeter-wave fast imaging system with a simple aperture operating as a microstrip transmission line etched with cELC metamaterial units. Each cELC unit has different resonant characteristics and can couple energy from the waveguide structure to free space, so a sequence of irrelevant field pattrens can be realized by controlling the input frequency. We use the frequency as the index of measurement matrix which is well satisfied the restricted isometry property(RIP) and well suited for compressive sensing. System operates in the Ka-band (27-40 GHz) with 4cm range resolution and 2 °of azimuth resolution.**

I. INTRODUCTION

MILLIMETER wave imaging plays an important role in many areas, such as safety inspection and medical diagnostics. Conventional MMW imaging systems often rely on mechanically scanning with single-pixel, which are typically inefficient at collecting data. Afterward, extensive research work has been done on the focal plane array and interferometry synthesis array systems because of their advantage of real time imaging and high resolution. But these systems suffer from the increased size, weight, and cost associated with the many receiving channels. Although the number of the receiving channels of interferometry synthesis array system is much less than that of the focal plane array, it needs tens at least.

Conventional single-pixel imaging system and focal plane array imaging system represent the two extremes of imaging styles. In 2008, Wai-Lam Chan[1] successfully developed a novel single-pixel imaging system in the form of compressive sensing[2], which was worked at terahertz frequency with the use of many random static masks. The single-pixel terahertz imaging system indicated that we can compress the data at physical layer to avoid redundant measurements in the imaging process. More recently, John Hunt's research has shown that metamaterial aperture can be used for coherent computational imaging at microwave frequency[3-5]. The single-pixel imaging system based on metamaterials has a trade-off between system coast and imaging time. More importantly, it successfully avoids mechanical switching of the mask.

In this work, we designed a simple and rapid imaging system based on metamaterials and compressive sensing theory, which is worked in the Ka-band. Because of the irrelevance of aperture's radiation characteristics in different frequency, we swept frequency to achieve multiple measurements. At last, we use the SP algorithm to reconstruct the scene.

II. IMAGING MODEL

Because of the diffraction limit, we divide the scene into N pixels and use a Ka-band horn antenna to illuminate the scene. When taking measurements, signals of different frequencies coupled by metamaterial cells from free space to the waveguide structure eventually reach the receiving port to form a measurement, and this measurement includes the all echo information of the imaging regions.

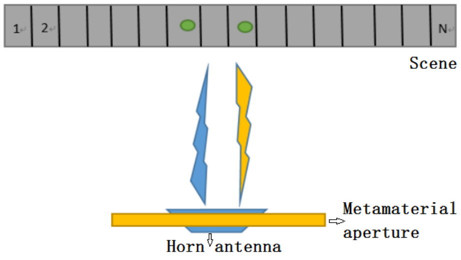


FIG. 1. IMAGING MODEL

The process can be expressed as:

$$E_d = \sum_{n=1}^{N} E_n^{tx} E_n^{rx} f_n = \begin{bmatrix} h_1 & h_2 & \cdots & h_N \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ \cdots \\ f_N \end{bmatrix}, h_n = E_n^{rx} E_n^{tx}$$

The E_d is the measurement at the receiving port, the E_n^{tx} and E_n^{rx} is the field distribution of the n^{th} region of the metamaterial aperture and the horn antenna. The vector of M (M<<N) measurements can be expressed in matrix notation as

$$\begin{bmatrix} E_1 \\ E_2 \\ \cdots \\ E_M \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & h_{22} & & \\ \vdots & & \ddots & \\ h_{M1} & & & h_{MN} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ \cdots \\ f_N \end{bmatrix}, h_{mn} = E_{mn}^{rx} E_{mn}^{tx}$$

and $g = H * f$.

In our experiment, the scene includes a few of point objects, so we can regard it as a sparse signal. With the knowledge of the compressive sensing theory, if the matrix H satisfied the restricted isometry property (RIP), we can reconstruct the scene by solving an optimization problem.

III. METAMATERIAL APERTURE

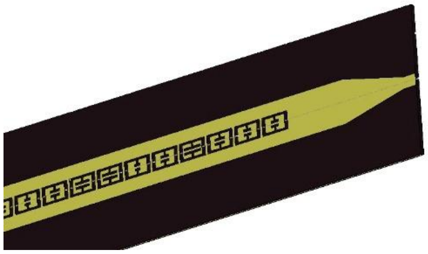
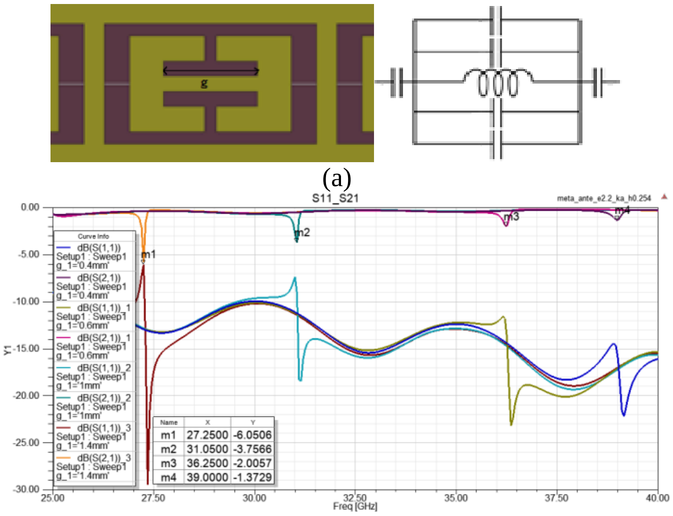


FIG. 2. METAMATERIAL APERTURE

The metamaterial aperture is a microstrip transmission line etched with complementary electric-lc (cELC) metamaterial units, shown in Fig.2. Each cELC unit has different resonant characteristics and can couple energy from the waveguide structure to free space. The equivalent circuit model of cELC is shown in Fig.3(a), We control the resonant frequency of it by changing the length of g between 0.4mm and 1.4mm, the Fig.3(b) shown the S-parameter of the aperture with different cELC unite.

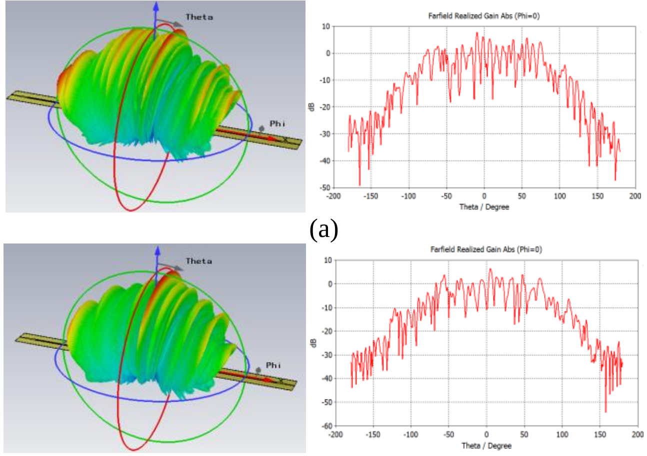


(a)

(b)

FIG. 3. THE EQUIVALENT CIRCUIT MODEL OF CELC (A) AND THE S-PARAMETER OF THE APERTURE WITH DIFFERENT CELC UNITE

The cELC of different resonant frequency distributed randomly in the microstrip transmission line, so a sequence of irrelevant field pattrens can be realized by controlling the input frequency. Fig.4 is the simulated 3D far-field and the H-plane pattern of the aperture at the frequency of 33 GHz (a) and 37 GHz (b).



(a)

(b)

FIG. 4. 3D FAR-FIELD AND THE H-PLANE PATTERN OF THE APERTURE AT THE FREQUENCY OF 33GHZ (A) AND 37GHZ (B)

IV. RESULTS

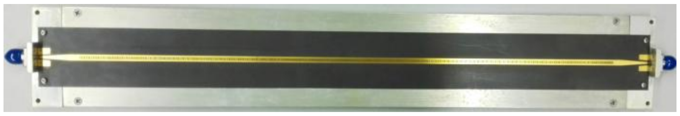


FIG. 5. FRONT OF THE METAMATERIAL APERTURE L

An aperture consisting of 130 cELCs was fabricated, which dimensions is 0.5cm × 3cm × 32cm. In theory, the azimuth resolution of the aperture at 33GHz is 1.9 ° and the range resolution is 1.1cm in the Ka-band.

We use the frequency as the index of measurement matrix, which is well satisfied the RIP. The row vector of the matrix is the magnitude and phase distributions at the scene plane in different frequency. The magnitude measurement matrix is plotted in Fig.6.

We measured the amplitude and phase of the signals of different frequencies with network analyzer, then the SP algorithm was employed to realize the reconstruction of sparse scene. In our experiment, system operates in the Ka-band with 4cm range resolution and 2 ° of azimuth resolution. Figure 2 depicts the reconstructed scene of 3 targets.

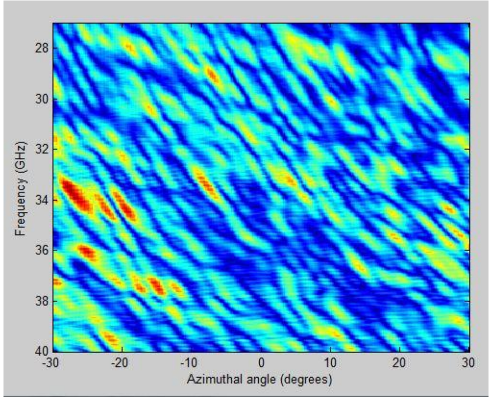


FIG. 6. MEASUREMENT MATRIX OF MAGNITUDE

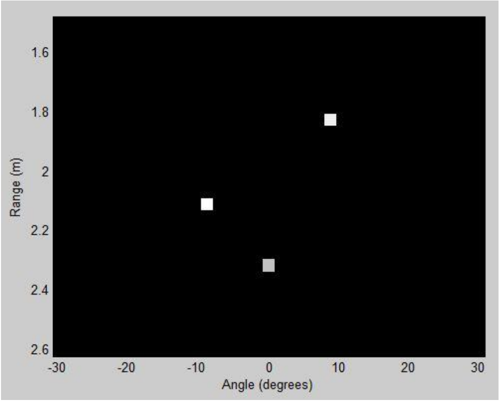


FIG. 7. RECONSTRUCTED SCENE OF 3 TARGETS

V. SUMMARY

We designed a simple and rapid imaging system based on metamaterials and compressive sensing theory, which is worked in the Ka-band with 4cm range resolution and 2 ° of azimuth resolution.

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