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A Single Pixel Millimetre-Wave Imaging System Based on Metamaterials

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Abstract—Based on metamaterials and compressive sensing theory, we design a single pixel millimeter-wave fast imaging system by a 1D aperture array. The aperture array is realized by a column of complementary electric-lc (cELC) units etched on a microstrip transmission line. Each cELC unit resonates at a different frequency, where the energy is coupled from the aperture to free space. A sequence of random field patterns can be obtained by controlling geometric parameters of each cELC unit. We use the frequency as the index of measurement matrix which well satisfies the restricted isometry property (RIP) and is well suited for compressive sensing (CS). A prototype of CS imaging system operating at Ka-band (27–40 GHz) is fabricated which can detect a 5 cm $*$ 5 cm object precisely at a distance of 50 cm.

1. INTRODUCTION

Millimetre-wave (MMW) 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 [1]. Afterward, extensive research work has been done on focal plane array and interferometry synthesis array systems because of their advantage of real time imaging and high resolution [2]. However, these systems suffer from relative large size, weight, and cost associated with many receiving channels. Although the number of receiving channels of an interferometry synthesis array system is much less than that of the focal plane array, it needs tens at least. Obviously, an efficient data processing method with fewer receiving channels and lower number of spatial samples is necessary for MMW imaging.

In 2008, Chan et al. [3] successfully developed a novel single-pixel imaging system in the form of compressive sensing [4], which works at THz frequency with the use of many random static masks. The single-pixel THz imaging system indicated that we can compress the data at physical layer to avoid redundant measurements in the imaging process. More recently, Hunt's research has shown that metamaterial aperture can be used for coherent computational imaging at microwave frequency [5–7]. The single-pixel imaging system based on metamaterials has a tradeoff between system coast and imaging time. More importantly, it successfully avoids mechanical switching of the mask.

In this work, we design a simple and rapid imaging system based on metamaterial aperture and CS theory, which works in Ka-band. Because of the irrelevance of aperture's radiation characteristics in different frequencies, we can achieve multiple measurements by sweeping the input frequency. At last, we use the SP algorithm to reconstruct the scene.

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2. MILLIMETRE-WAVE COMPRESSIVE SENSING IMAGING MODEL

As shown in Fig. 1, in a millimetre-wave CS imaging system, the receiving aperture with different random field distributions illuminates and samples a different portion of the imaging area. This measurement includes all echo information of the scene.

The set of signals received by the antenna can be expressed as:

$$g = H * f$$

where, H is the system transfer matrix which called measurement matrix, and f is the needed reflectivity of the scene. Because of the diffraction limit, we divide the scene into N pixels and according to the propagation characteristics of a wave in free space:

$$H = \begin{bmatrix} E_{11}^{rx} & E_{12}^{rx} & \cdots & E_{1n}^{rx} \\ E_{21}^{rx} & E_{22}^{rx} & & \\ \vdots & & \ddots & \\ E_{m1}^{rx} & & & E_{mn}^{rx} \end{bmatrix}$$

E_{mn}^{rx} is the m time field distribution at the nth region of the antenna. By solving a minimization problem:

$$f = \arg\min_{f} \|g - Hf\|_2^2 + \mu\|f\|_1$$

We can reconstruct the needed f, even though the number of measurements M is much lower than the number of the scene data N.

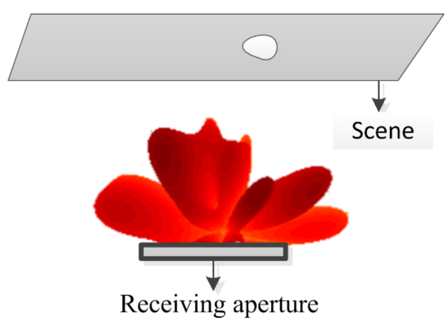


Figure 1. Schematic of CS imaging.

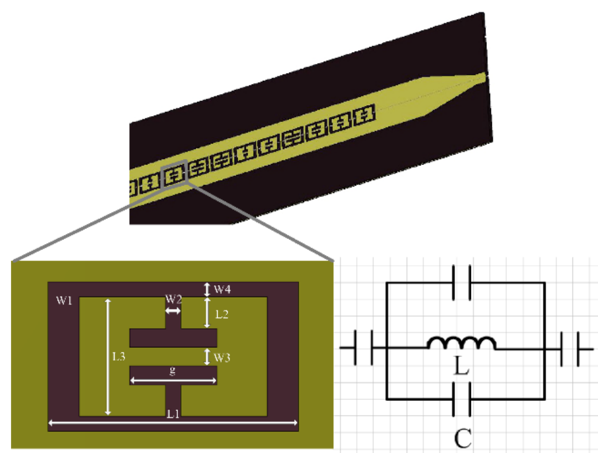


Figure 2. The structure of metamaterial aperture and equivalent circuit model of cELC unit.

3. METAMATERIAL APERTURE DESIGN

The essential component of a CS imaging system is an aperture that generates diverse patterns of radiated fields that sequentially sample the scene which is called measurement modes. In this paper, the metamaterial aperture is a column of complementary electric-lc (cELC) metamaterial units etched in a microstrip transmission line, as shown in Fig. 2. Each cELC unit behaves similarly to the dual magnetic resonators of complementary split-ring-resonator (cSRR) with different resonance characteristics [8], and strong electric field will be coupled and radiate in a narrow band around the resonance frequency. The equivalent circuit model of the cELC unit is similar to the common electric-lc (ELC) unit with a swapped inductance and capacitance. Each of the inductance and capacitance values is affected by the length and width of the gap.

The cELC aperture essentially behaves as a cascaded LC bandpass network for free-wave propagation, and the geometric parameters affect the value of the inductance and capacitance, which can be used to adjust the resonance characteristics of the LC bandpass network. The resonance frequency and Q-factor of the equivalent circuit are:

$$f = 1/\sqrt{LC} \tag{1}$$

$$Q = R^{-1}\sqrt{L/C} \tag{2}$$

The radiation resistance R is small compared to L and C, so the changes of L and C are the main factors of the resonance shift. In order to maximize the Q-factor of the cELC unit, we set the geometric parameters as $w2 = w4 = 0.12$ mm, which is the fabrication limit of print circuit board technology. Other detailed dimensions are: $w1 = 0.25$ mm, $w3 = 0.15$ mm, $L1 = 2$ mm, $L2 = 0.25$ mm and $L3 = 0.95$ mm. The resonance frequency can be controlled by changing the parameter of g from 0.4 mm to 1.4 mm, covering the entire Ka-band, as shown in Fig. 3. Each value of g results in a unique resonance characteristic, and energy at the resonance frequency can be coupled and radiated from the aperture to free space.

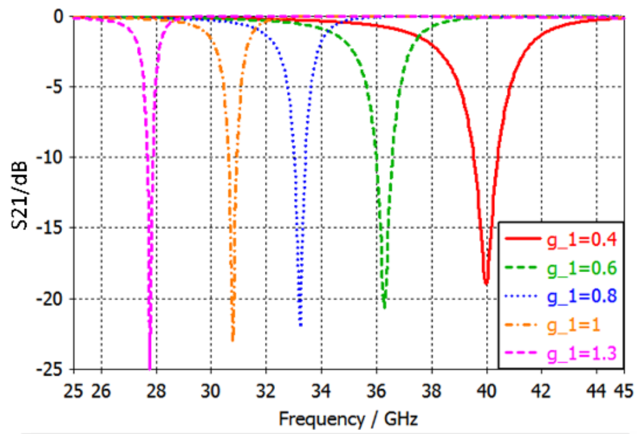
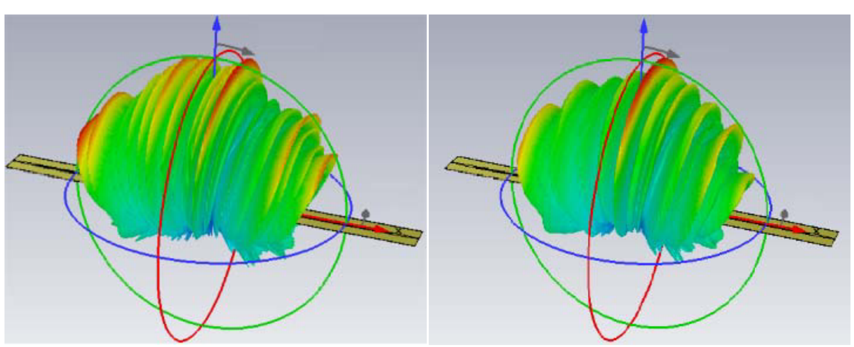


Figure 3. The resonance frequency of cELC unit with different length of g.

The cELC units with different resonance frequencies are designed to be distributed randomly in the microstrip transmission line, so a sequence of irrelevant field patterns can be obtained by controlling the input frequency. Fig. 4 is the simulated 3D far-field of the aperture at the frequency of 33 GHz and 37 GHz.



(a) (b)

Figure 4. 3D far-field of the aperture at the frequency of (a) 33 GHz and (b) 37 GHz.

4. EXPERIMENT RESULTS

An aperture consisting of 130 cELCs is fabricated, which is shown in Fig. 5, and the dimensions are $0.5\,\text{cm} \times 3\,\text{cm} \times 32\,\text{cm}$.

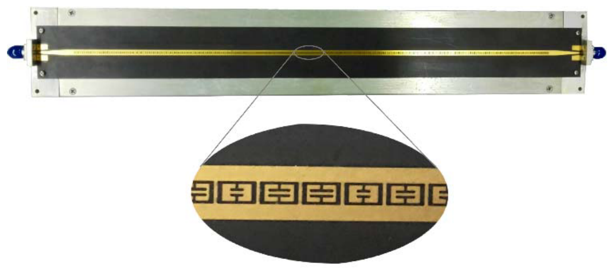


Figure 5. Photograph of fabricated metamaterial aperture.

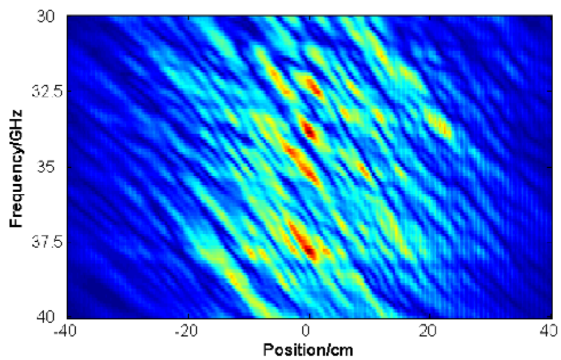


Figure 6. Measurement matrix of magnitude.

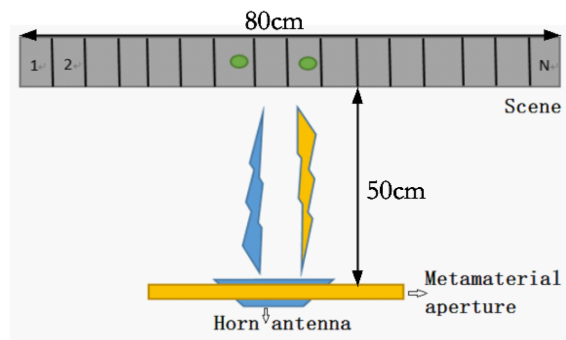


Figure 7. Imaging model.

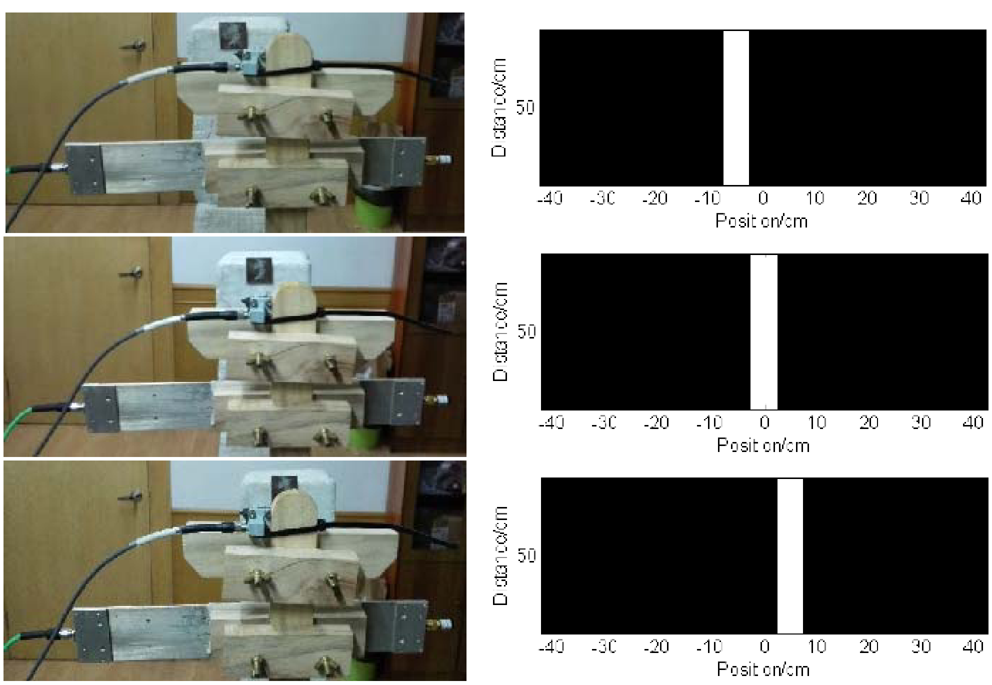


Figure 8. Reconstructed scene of one target at the different position.

A vector network analyser (VNA) Agilent N5224A is used to feed the metamaterial aperture and to measure the field distributions over the band from 30 GHz to 40 GHz at the distance of 50 cm away from the aperture. We use the frequency as the index of measurement matrix, which well satisfies the RIP. The row vector of the matrix is the magnitude and phase distributions at the scene plane in different frequencies. The magnitude measurement matrix is plotted in Fig. 6.

Fig. 7 shows the imaging model of the system. We use a Ka-band horn antenna as the radiation source to illuminate the scene which is 50 cm away from the antenna. The metamaterial cells couple the echo signals at different frequencies from free space to the waveguide structure, eventually reach the receiving port to form a measurement, and this measurement includes all the echo information of the imaging regions. We measure the amplitude and phase of the signals of different frequencies by VNA.

The target is a metal plate of $5\,\mathrm{cm} * 5\,\mathrm{cm}$ and placed at different positions of the scene which is divided into 17 pixels. After taking measurements, the SP algorithm is employed to reconstruct the sparse scene. Fig. 8 depicts the reconstructed scene of one target at different positions. It can be seen that the system operating at Ka-band can detect a $5\,\mathrm{cm} * 5\,\mathrm{cm}$ object precisely at the distance of 50 cm.

5. CONCLUSION

We design a simple and rapid imaging system based on metamaterials and compressive sensing theory, which works in Ka-band. By controlling the input frequency, the metamaterial aperture can generate a sequence of irrelevant field patterns to sample the scene. Each measurement includes all echo information, thus we can use SP algorithm to reconstruct the scene. The experimental results show that the aperture can detect a $5\,\mathrm{cm} * 5\,\mathrm{cm}$ object precisely at the distance of 50 cm.

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