Researches on Far-Field Super-Resolution Imaging Based on Time-Reversed Electromagnetics at UESTC

by

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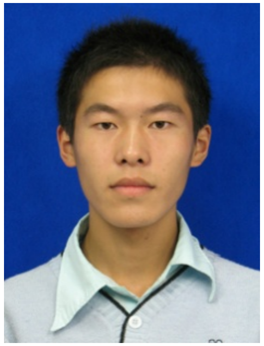
Abstract

Time reversal (TR) of electromagnetic waves exhibits temporal and spatial focusing. Based on this characteristic, TR technique has found potential applications in super-resolution imaging. This poster simply gives an overview on far-field super-resolution imaging based on TR technique at University of Electronic Science and Technology of China (UESTC) in recent years.

Keywords: Far-field, super-resolution, time reversal

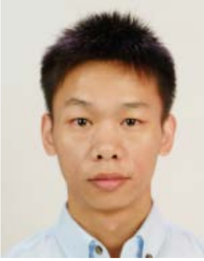
Biography

Bing-Zhong Wang received the Ph.D. degree in electrical engineering from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 1988. He joined UESTC in 1984, where he is currently a Professor. He has been a Visiting Scholar at the University of Wisconsin-Milwaukee, Milwaukee, WI, USA, a Research Fellow with the City University of Hong Kong, Kowloon, Hong Kong, and a Visiting Professor at the Pennsylvania State University, University Park, State College, PA, USA. His research interests include the areas of computational electromagnetics, antenna theory and techniques, and time-reversed electromagnetics.



Ren Wang was born in Anhui Province, China, in 1990. He received the B.S. degree in electronic information science and technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2014. Currently, he is working toward the Ph.D. degree in radio physics at UESTC. His research interests include time-reversed technique, compact multiport antenna, and phased array.

Biography



Zhi-Shuang Gong was born in 1991, in Jiangxi, China, where he received his early education. He received the B.S. degree in vacuum electronics from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2012. He is now a Ph.D. student in radio physics at the UESTC. His research interests include time reversal theory, far-field super-resolution imaging and antenna theory.

Qiang Gao was born in Anhui Province, China, in 1990. He received the B.S. degree in electronic information science and technology and M.S. degree in radio physics from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2012 and 2014, respectively. He is currently pursuing the Ph.D. degree in radio physics at UESTC. His research interests include time-reversed technique, super-resolution imaging, and periodical structures.

Xiao-Hua Wang was born in Jiangsu, China, in 1980. He received the B.S., M.S., and Ph.D. degree from University of Electronic Science and Technology of China (UESTC) in 2002, 2005, and 2008, respectively. From Mar. 2008 to Feb. 2009, he was a RF research engineer in Huawei Company. From Mar. 2009 to Feb. 2010, he was with the Department of Electronic Engineering, City University of Hong Kong as research staff. Now, he is an associate professor at UESTC. His research interests include: computational electromagnetics, microwave passive circuits, and antenna design.

1. Introduction

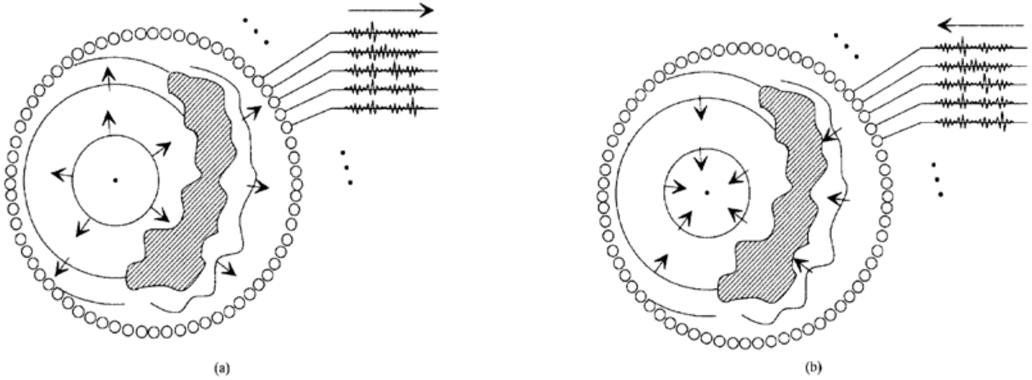


Fig. 1. TR process by Fink (a)forward and (b)reversal process.

◆ **Time-reversal (TR) propagation process**

➢ Step 1 Place an initial excitation source, $\delta(\mathbf{r}-\mathbf{r}_s)\mathbf{i}(\omega)$.

The radiated fields can be expressed as

$$\boldsymbol{E}(\mathbf{r},\mathbf{r}_s)\big|\mathbf{r}\in S = -j\omega\mu\overline{\overline{G}}(\mathbf{r},\mathbf{r}_s)\mathbf{i}\Big|\mathbf{r}\in S$$

➢ Step 2 Reverse the received signals in time axis (equal to the conjugation in frequency)

$$\boldsymbol{E}^*(\mathbf{r},\mathbf{r}_s)\big|\mathbf{r}\in S = j\omega\mu\overline{\overline{G}}^*(\mathbf{r},\mathbf{r}_s)\mathbf{i}^*\Big|\mathbf{r}\in S$$

➢ Step 3 Emit the reversed signals. So the TR field is

$$\boldsymbol{E}^{TR}(\mathbf{r},\mathbf{r}_s;\omega) = j\omega\mu\left\{\overline{\overline{G}}^*(\mathbf{r},\mathbf{r}_s)-\overline{\overline{G}}(\mathbf{r},\mathbf{r}_s)\right\}\boldsymbol{i}^*(\omega)$$

1. Introduction

- TR electromagnetic wave characteristics: **spatial-temporal focusing**
  - $h(t)*h(-t)$ → temporal focusing
  - $\left\{\left(\overset{=}{I}+\frac{\nabla\nabla}{k^2}\right)\left(\frac{\sin k\left|\boldsymbol{r}-\boldsymbol{r}_s\right|}{k\left|\boldsymbol{r}-\boldsymbol{r}_s\right|}\right)\right\}\boldsymbol{i}^*(\omega)$ → spatial focusing
- Applications: location, high power system, green communication, imaging, *etc.*

2. Super-Resolution Imaging Based on TR Algorithms

◆Time Domain Imaging Methods:

➢TR mirror/ Iterative TR mirror (Fink)

✓Focusing on the strongest scatter

➢TR adaptive interference cancellation (Moura)

✓Cancelling the noise clutters' effects

◆Frequency Domain Imaging Methods on TR operator:

(1) Received signal by TRMs:

$$R_0(\omega) = H(\omega) E_0(\omega)$$

(2) Received signal after TR:

$$R_1(\omega) = \left\{ H^T(\omega) H^*(\omega) \right\} E_0^*(\omega)$$

➢ TR operator (TRO): $T(\omega) = H^H(\omega) H(\omega)$

➢ TRO contains a lot of information, such as the characteristics of targets

2. Super-Resolution Imaging Based on TR Algorithms

◆Decomposition of TRO

- Eigenvalue decomposition of T:

$$T = V\Sigma^2 V^H = [V_S, V_N]\begin{bmatrix} \Sigma_s^2 & 0 \\ 0 & 0 \end{bmatrix}[V_S, V_N]^H ; Tu_j = \lambda_j u_j$$

- Vectors in the signal subspace: corresponding to the Green's function vector of the target's position.
- Vectors in the noise subspace: **orthogonal** to the Green's function vector of the target's position.

◆DORT Method (based on signal subspaces)

The imaging pseudo-spectrum by the signal subspace:

$$P_{tm-dort} = \sum_{\sigma_j \neq 0} \sum_{i=1,2,3} \left[\left| u_j^{\dagger} \overline{\boldsymbol{B}}_i(\boldsymbol{r}) \right|^2 + \left| u_j^{\dagger} \overline{\boldsymbol{X}}_i(\boldsymbol{r}) \right|^2 \right]$$

At the target position, the inner product is **maximum**.

- Advantages: stable, high efficiency
- Disadvantages: low resolution

2. Super-Resolution Imaging Based on TR Algorithms

◆TR MUSIC Method (based on noise subspaces)

The formula of pseudo-spectrum by the noise subspace:

$$P_{tm-music}(\boldsymbol{r}) = \frac{1}{\sum\limits_{\sigma_j=0} \left\{ \left[\sum\limits_{i=1,2,3} \left| u_j^{\dagger} \overline{\boldsymbol{B}^t}_i(\boldsymbol{r}) \right|^2 + \sum\limits_{i=1,2,3} \left| u_j^{\dagger} \overline{\boldsymbol{X}^t}_i(\boldsymbol{r}) \right|^2 \right] + \left[\sum\limits_{i=1,2,3} \left| \upsilon_p^T \overline{\boldsymbol{B}^r}_i(\boldsymbol{r}) \right|^2 + \sum\limits_{i=1,2,3} \left| \upsilon_j^T \overline{\boldsymbol{X}^r}_i(\boldsymbol{r}) \right|^2 \right] \right\}}$$

At the target position, noise subspace eigenvectors and background Green's function vectors are orthogonal. The value will tend to **infinity**, and at non target position, it is a **finite value**. So from the spectrum image, the target location can be labeled and with **high resolution**.

- ➢ Advantage: high resolution
- ➢ Disadvantages: sensitive to noise, more imaging time and memory cost

2. Super-Resolution Imaging Based on TR Algorithms

◆ **TR-MUSIC of Transmission Mode**

It can obtain more accurate location and higher resolution due to the increased effective aperture when compared with echo mode.

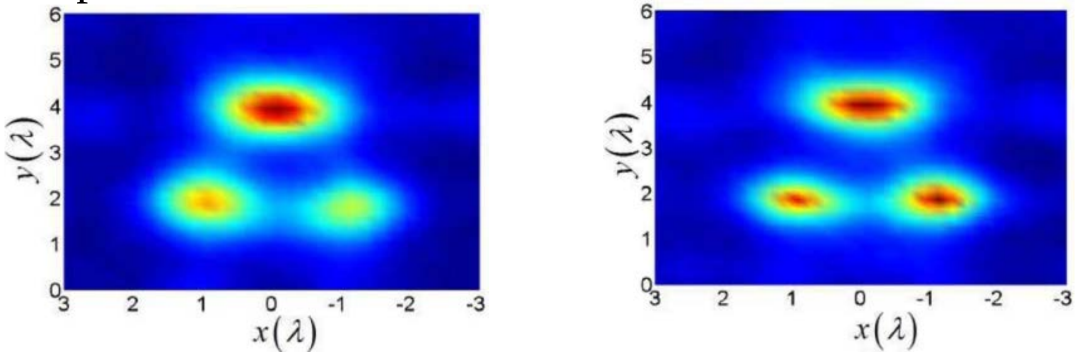


Fig. 2. TR-MUSIC of (a)echo mode, (b)transmission mode.

The results will be good when one target blocks the other.

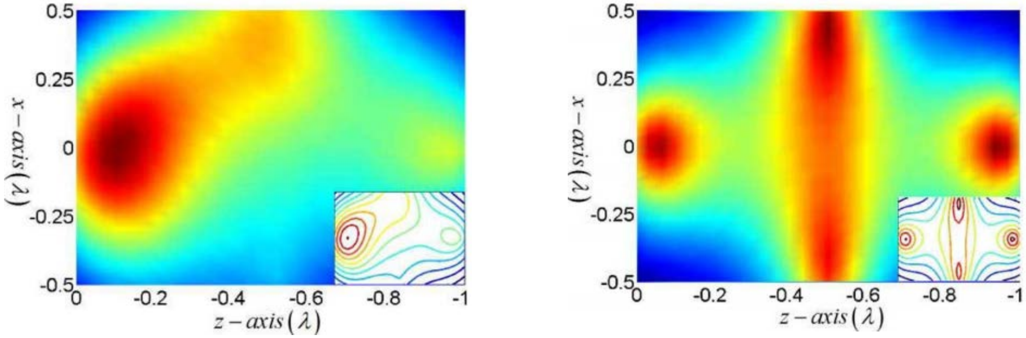


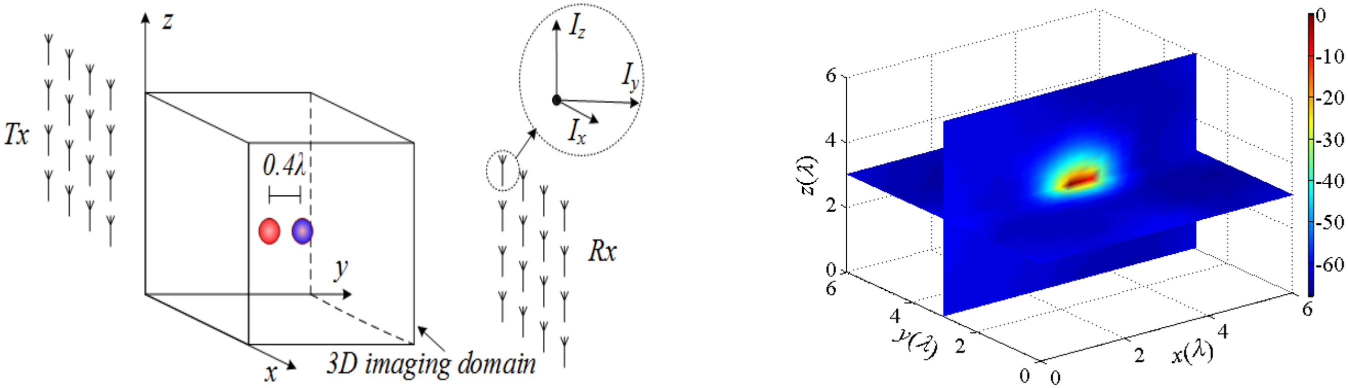
Fig. 3. TR-MUSIC of (a)echo mode,(b)transmission mode.

2. Super-Resolution Imaging Based on TR Algorithms

- Hybrid method (DORT+TR-MUSIC) for efficiency

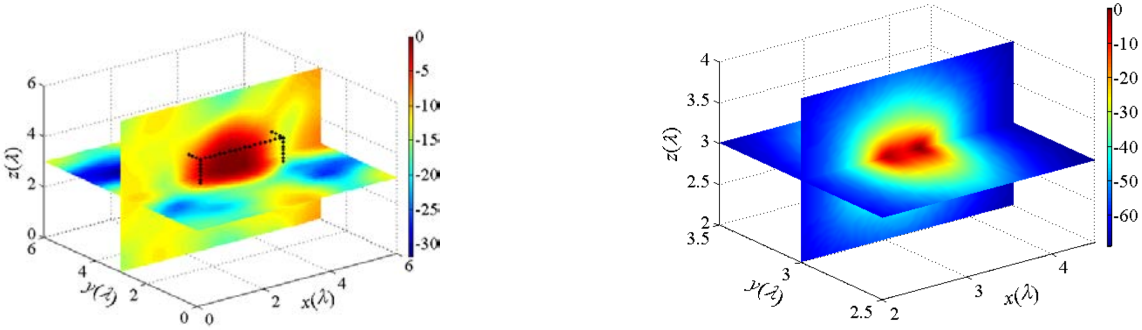
Step I: Employing DORT in the whole domain with lower resolution to **get a primary estimation** of the targets **with little CPU time and memory cost**.

Step II: Employing TR-MUSIC in the estimated target area to **get a super resolution image** of the targets beyond the diffraction limit.

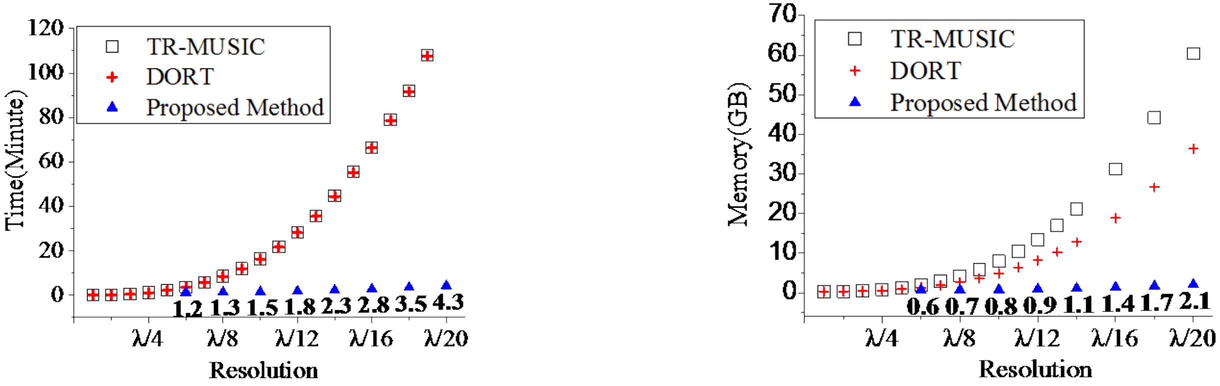


(a) configuration of imaging model (b) the imaging by TR-MUSIC

2. Super-Resolution Imaging Based on TR Algorithms



(c) Step I by DORT with λ/4 (d) Step II by TR-MUSIC with λ/20



(e)CPU time (f)Memory cost

Fig. 4 Hybrid method

3. Super-Resolution Imaging with Auxiliary Structures

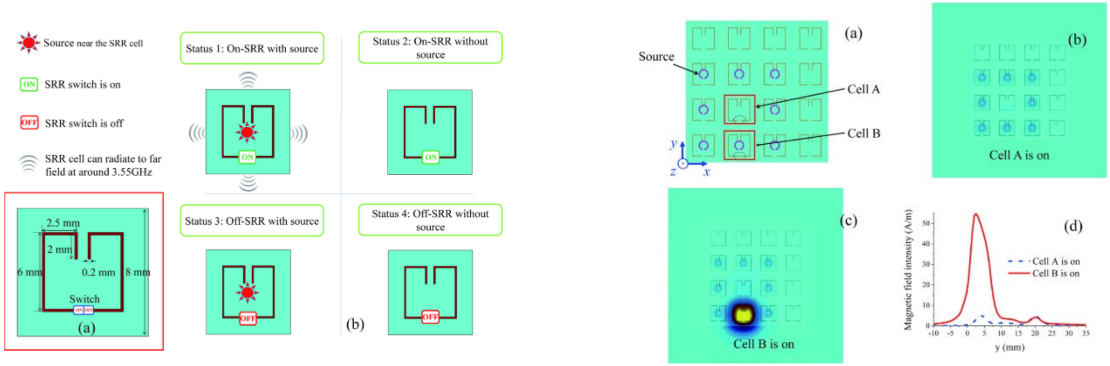
◆ **Possible ways for far-field super-resolution Imaging**

- Rayleigh Criterion (~λ/2): operate only with propagation waves and lose evanescent waves
- **How to dig out the sub-wavelength information?**
  - Scattering central location algorithms (**TR-MUSIC**)
  - Scattering central measurement method (**SRRs with switches**)
  - Time-reversal focusing method (**Planar Resonant Lens**)

◆ **Scattering central measurement method**

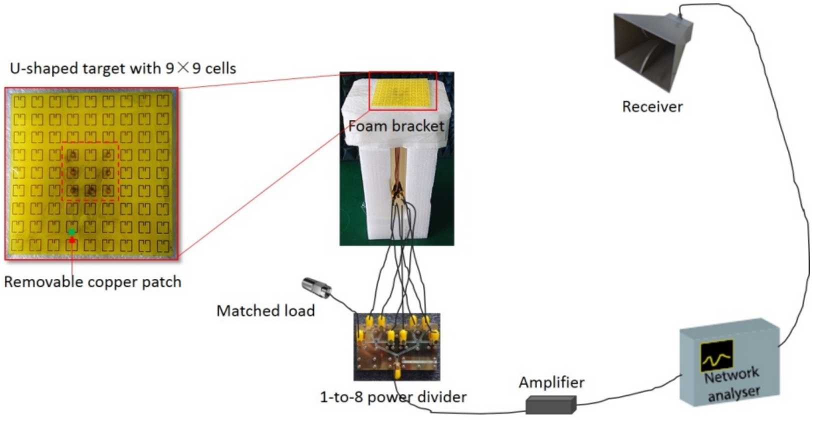
- “**near-field super-resolution scanning + radiation propagation + far-field receiving**”
- **Key technology：near-field resonance super lens scanning**
  - The super lens with local resonance can convert the evanescent mode to the propagation mode, and make the surface field be limited to a small local area.

3. Super-Resolution Imaging with Auxiliary Structures



(a)SRR cell with switch

(b)Magnetic field pattern



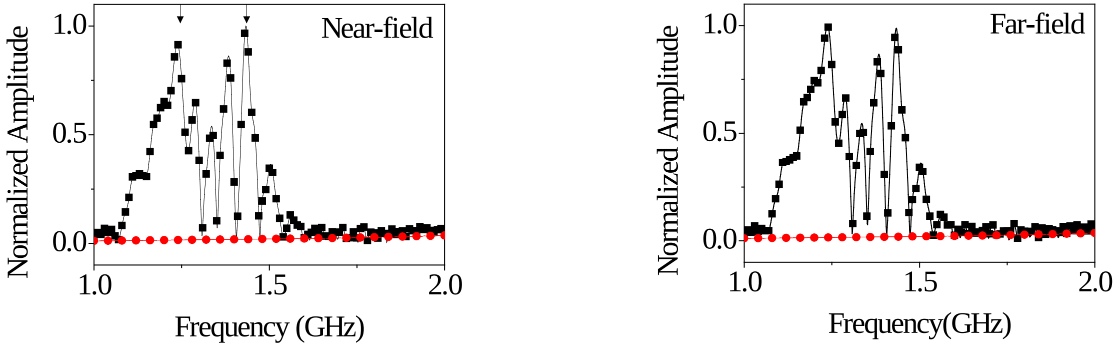
(c) Experimental photo

Fig. 5. Near-field resonance SRR lens scanning method

3. Super-Resolution Imaging with Auxiliary Structures

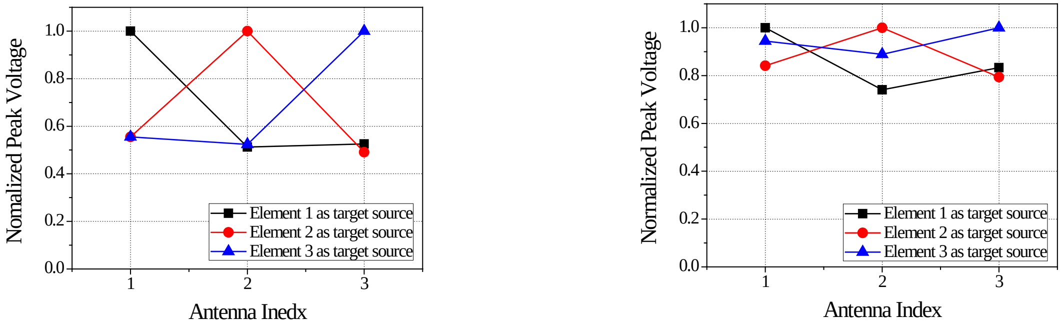
◆ **The time-reversed focusing method**

- “**near-field evanescent wave coupling + radiation propagation + far-field receiving**”
- **Key technology：near-field mode converter**
  - Aided by the PRLs, the conversion between evanescent-propagation mode can be realized. Therefore, the sub-wavelength information, carried on the propagation wave, can be radiated to the far-field.
  - Back propagation the received signals based on the time-reversal method, it can be realized the far-field super-resolution imaging for the spatial-temporal focusing property of TR.

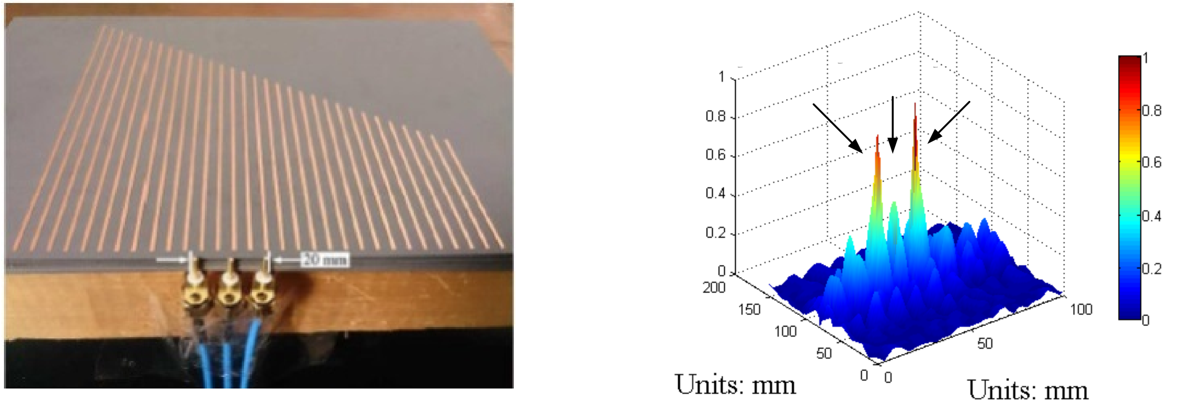


Numerical simulation results of spectra (a) near- (b)far-field

3. Super-Resolution Imaging with Auxiliary Structures



Normalized experimental peak voltage(c)with (d)without PRLs



(e)Photo of PRLs (f) Simulation of source imaging

Fig. 6. TR imaging method with PRLs.

4. Conclusion

- This poster simply gives an overview on far-field super-resolution imaging based on TR technique at UESTC in recent years from two aspects of imaging algorithms and transforming structures, respectively. In the aspect of TR algorithms, recent researches focus on increasing efficiency under the condition of high resolution. In the aspect of transforming structures, how to transport information of evanescent waves to far-field is the research priority. Up to now, the two aspects were researched separately. Effectively combining algorithms and structures to realize a super-resolution imaging system is a valuable direction.

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Thanks !