Super-resolution and Frequency Spectrum Characteristics of Micro-structured Array Based on Time Reversal Electromagnetic Wave

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Abstract-**This paper has a research on super-resolution and frequency spectrum characteristics of micro-structured array. It proposes a model with different distributions of thin metal wires placed around coaxial probes to verify the filter effect of loaded metal wires on signal frequency spectrum. With time reversal technique, it has been proved that under random loaded metal wires, single-frequency signals have the same super-resolution focusing properties with the broadband signals. Additionally, this paper analyzes and concludes the variation of signal spectrums as well as the effects on super-resolution performance for different uniform distributions of wires. The analyzed and simulated results have important guiding significance to the modeling, quantifiable design and analysis of novel micro-structured array used in multi-antenna wireless communication system with super-resolution characteristics.**

I. INTRODUCTION

In order to further improve the capacity and rate of wireless communication, compact antenna array adapted in mobile station has received wide attention in recent years, which owns independent channels and spacing much smaller than wavelength. Constructing the technique of super-resolution transmission of electromagnetic waves is important to achieve multi-independent channels in compact space of mobile station. The earliest study of super-resolution phenomenon began with sub-wavelength optical imaging [1-2], which got super-resolution characteristics through probing the high frequency components corresponding with the fine structures of objects in near field. In 2002, Rosny found super-resolution phenomenon in near field by using time reversal (TR) acoustic [3]. TR technique was introduced in electromagnetic fields in 2004 [4]. In 2007, the super-resolution focusing characteristics of far field can be achieved by TR electromagnetic wave in a rich multi-path environment introduced in [5]. Ref. [5] used a type of micro-structured antenna array with /30 spacing which converted evanescent wave to propagating wave to build multi-channel and high-speed wireless communication system. Although the research shows it is possible to construct the compact antenna array in compact space, there is no related design theory of micro-structured antenna array. In 2009, G. D. Ge had done some preliminary explorations about factors which had influences on super-resolution transmission characteristics of TR electromagnetic wave [6]. It is given that the multi-path effect caused by micro-structures is the critical factor to realize super-resolution characteristics. According to the conclusion, kinds of sub-wavelength antenna arrays etched with different micro-structures were analyzed and designed in [7]-[9], which could be used for high-speed multi-antenna communication systems under TR technique. However, these researches did not find and build general design method of related micro-structures which were designed randomly. So it is necessary to deeply study the interaction principles between micro-structured antenna and electromagnetic field for modeled and quantifiable design of compact multi-antenna system.

This paper takes coaxial probe antennas loaded with thin metal wires as the research object to explore the interaction principles between micro-structured antennas and electromagnetic field. The influence of thin metal wires on frequency response characteristics of radiated signal has been analyzed by comparing the radiation results of different distributions of loaded wires with that of no wires. Based on the antenna model loaded with random thin metal wires, focusing transmission characteristics of single and wide frequency signals has been studied as well as the influences of micro-structures loaded with different distributions of uniform thin metal wires on radiated signals and super-resolution transmission performance. According to these studies, this paper achieves many principles about the interaction between sub-wavelength micro-structured antenna and electromagnetic wave, which have important guiding significance to modeling analysis and quantifiable design of micro-structured antenna array.

II. SIMULATION AND ANALYSIS OF THIN METAL WIRES STRUCTURES

The frequency response characteristics of the interaction between thin metal wires structures and electromagnetic wave is the basis to understand the property of micro-structured antennas. This paper firstly analyzes the problem with or without thin metal wires placed around the probe antennas as the research object.

As shown in Fig. 1(a), the simulated prototype is placed in open space. The used frequency spectrum band of Gaussian modulated pulse signal is from 2 to 6GHz. The details of the probe array are sketched in Fig. 1(b) which consists of five coaxial probes $\lambda/15$ apart from one other numbered 1 to 5, where λ is the wavelength of the central frequency 4GHz. The length of coaxial probe is λ/4. The probe array is 3λ away from the time reversal mirror (TRM), which consists of three bowtie antennas λ/2 apart from one other numbered 6 to 8 [7]. Here, CST Microwave Studio commercial software is used to simulate the prototype.

To discuss the influences on signal frequency spectrums which TRM receiced under differrent ways of loading thin metal wires, the simulation content contains as follows:

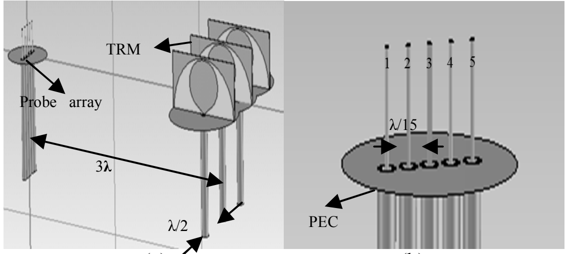
(1) no wires distributed around probes, as shown in Fig. 1(b);

(2) random distribution of thin metal wires around probes, as shown in Fig. 2(a), the length and radius of wires are 0.6λ and λ/500, respectively;

(3) uniform distribution of wires as shown in Fig. 2(b), the spacing of wires is λ/25, the features of wires are the same to 2th content. There are twelve wires around every wire.

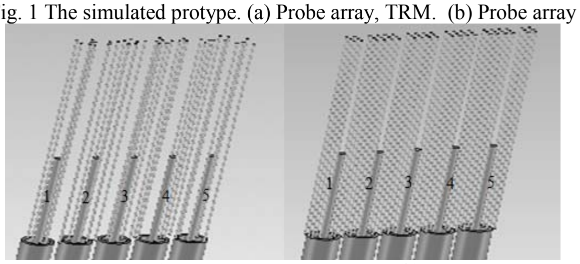
The simulation procedure can be described as follows: a pulse signal $i(t)$ which frequency band is from 2 to 6GHz is transmitted from the 3th probe antenna and the signal received at m th bowtie antenna of the TRM is denoted as $r_m(t)$ m=(6,7,8). The procedure is applied to all three contents. To further investigate the filter effect of the thin metal wires, we use the normalized frequency spectrum amplitude of $r_m(t)$ to compare with the normalized frequency spectrum of the input signal, as shown in Fig. 3(a)-(c).

According to the results shown in Fig.3 (a)-(c), the frequency spectrums received at TRM are relatively uniform and smooth in Fig. 3(a). By comparing Fig. 3(b) with Fig. 3(c), it shows that the selected frequency performance at specific frequency points under random distribution is more obvious than that of uniform distribution. This phenomenon can be explained that period structures formed by uniform loaded metal wires show band-gap characteristics at specific frequency points, while non-period structures formed by random loaded wires have wider stop-band characteristics which show the property of narrower selected frequency.



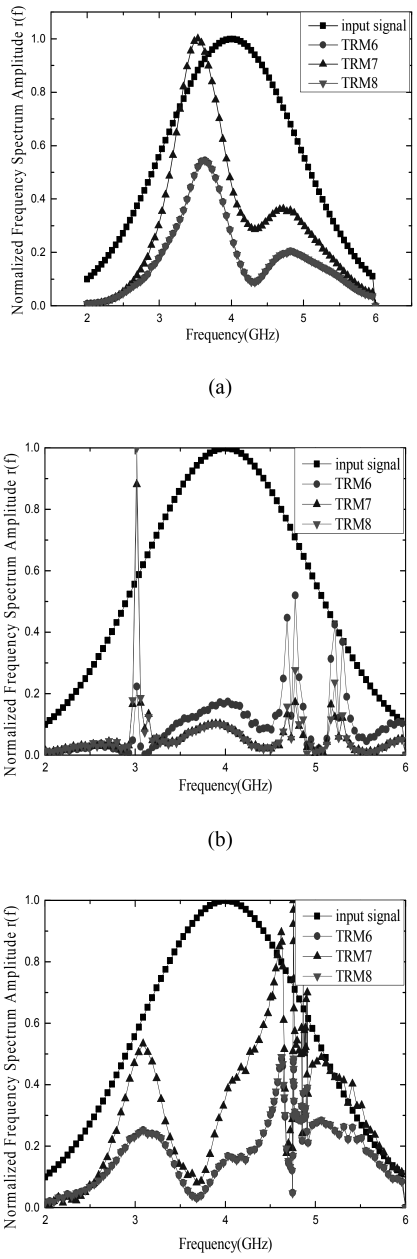
(a) (b)

Fig. 1 The simulated protype. (a) Probe array, TRM. (b) Probe array



(a) (b)

Fig. 2. Micro-structured array. (a) Random distribution. (b) Uniform distribution



(a)

(b)

(c)

Fig. 3. Signal frequency spectrum distribution. (a) No thin metal wires. (b) Non-uniform distribution. (c) Uniform distribution

III. SIMULAITION AND ANALYSIS OF SUPER-RESOLUTION FOCUSING

Under TR technique, in order to determine the influence of the single frequency point corresponding to the peak of frequency spectrum received at 3th antenna based on the micro-structured array shown in Fig. 3(b) on super-resolution property, the simulation content contains as follows: the frequency bandwidth of input signal which 3th antenna transmits are 3.02GHz and 2-6GHz, respectively.

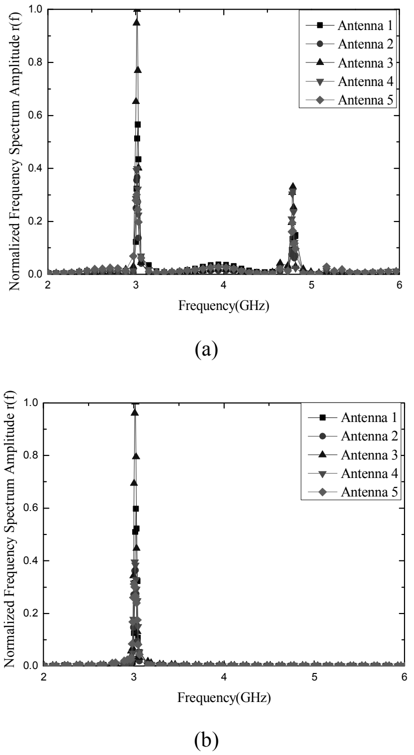
The simulation procedure can be described as follows:

firstly, a pulse signal $i(t)$ is transmitted from the 3th probe antenna and the signal received at m th bowtie antenna of the TRM is denoted as $r_m(t)$ (m=6,7,8). Secondly, $r_m(t)$ is reversed by first-in-last-out way to get $r_m(-t)$. Thirdly, each signal is retransmitted back from the m th bowtie antenna to the micro-structured array at the same time. The same procedure is also applied to single frequency signal, frequency of which is at 3.02GHz. We denote the signals received at the n th micro-structured antenna as $r_n^{TR}(t)$ (n=1, 2, 3, 4, 5). To observe super resolution characteristics after TR clearly, we use the Parserval theorem to express the signal energy in frequency domain:

$$P_n = \sum_k \left| r_n^{TR}(f_k) \right|^2 \times \Delta f \qquad (k = 1, 2, \cdots) \tag{1}$$

where n is the number of micro-structured array, and $\left| r_n^{TR}(f_k) \right|$ is the frequency spectrum amplitude at frequency f_k, which corresponds to the uniform sampling frequency points between 2GHz and 6GHz. Δf is the interval of uniform sampling. P_n is the energy of the signal received at the n th micro-structure antenna in the specified frequency bandwidth. To analyze frequency spectrum and super resolution characteristics, we draw out the normalized frequency spectrum amplitude of $r_n^{TR}(t)$ (n=1, 2, 3, 4, 5) and P_n (n=1, 2, 3, 4, 5) of two simulation results, as shown in Fig.4 (a)-(b) and Fig. 5.

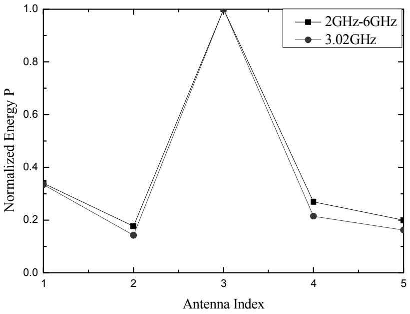
According to the results shown in Fig. 4(a), it is clear that the signal frequency spectrums received at probe array are still narrow-band when the model uses random distribution combined with TR technique. As shown in Fig. 5, energy of the n th (n=1, 2, 4, 5) antenna is 33% lower than the energy of 3th antenna. It could be concluded that the micro-structured array shows super-resolution characteristics clearly and the single frequency point contributes the majority of energy to make the model show super-resolution performance. So under non-period random loaded thin metal wires, the narrow frequency spectrum resulted from the narrow-band characteristics of structures can achieve good super-resolution focusing property. And current literatures show that related researches focus on super-resolution focusing field of ultra-wideband time reversal electromagnetic signal.



(a)

(b)

Fig. 4. Signal frequency spectrum distribution. (a) Bandwidth is from 2GHz to 6GHz. (b) Single frequency at 3.02GHz



(c)

Fig. 5. Results for different input signals

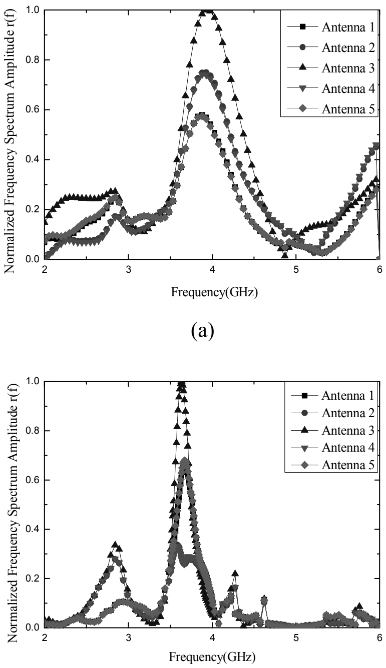
IV. SIMULATION AND ANALYSIS OF DIFFERENT MICRO-STRUCTURES

Under uniform distributions, we denote the length of thin metal wires as l and the spacing of wires as d . To discuss influences of the two variables on signal frequency spectrums and super-resolution characteristics which received at the n th (n=1, 2, 3, 4, 5) antenna, this part simulates different metal wires structures with different variable values. The probe array spacing in Fig. 1(b) turns to be λ/4 to make the variable d to take more values.

Based on the model shown in Fig. 1, we simulate six models as follows: when l is fixed to 0.6λ, d is changed to λ/75, 2λ/75 and λ/25, respectively; when d is fixed to λ/25, l is changed to 3λ/5, 2λ/5 and λ/5, respectively. The simulation procedure is the same with part III.

Because of the limited space, we only list the normalized frequency spectrum amplitude of two models which have the best super-resolution characteristics, as shown in Fig. 6(a)-(b). And the normalized P by the energy of the 3th antenna of the six models are showed in Fig. 7(a)-(b), respectively.

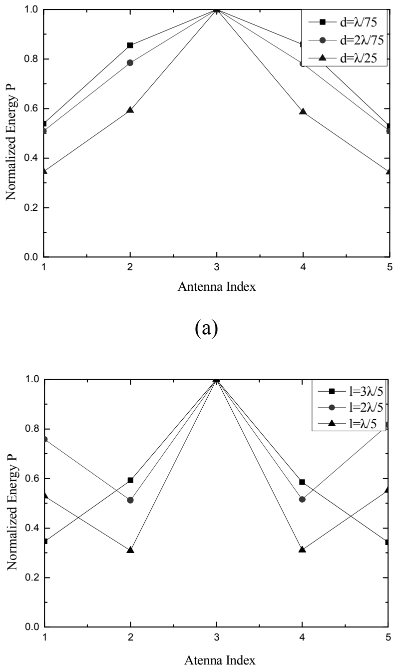
According to Fig. 5(a), it shows that the signal frequency spectrum received at 3th antenna is clearly different from others. So it is in Fig. 6(a). But when Fig. 6(a) is compared to Fig. 5(a), it has the property of narrow band. Fig. 5(b) and 6(b) show that models with $l = 3\lambda/5$, $d = \lambda/25$ and $l = \lambda/5$, $d = \lambda/25$ have the property of super-resolution at the target antenna which is numbered 3, because the energies of other antennas are all nearly below 50%. When d inceases or l reduces, the coupling effects among probe antennas will decease, thus the super-resolution property gets more clearly. As the length and spacing of thin metal wires vary, the frequency point corresponding to the peak of signal frequency spectrum received at 1-5 th antenna will take some offsets. In a word, the variables have effects on wideband and super-resolution characteristics of the models. So by analyzing the two variables, we can find out a model to meet the design requirements.



(a)

(b)

Fig. 6. signal frequency spectrum distribution. (a) *l* = 3/5λ, *d* = λ/25. (b) *l* = λ/5, *d* = λ/25.



(a)

(b)

Fig. 7. results for different varible. (a) *l* is fixed to 3λ/5, *d* is changed to λ/75, 2λ/75 and λ/25, respectively; (b) *d* is fixed to λ/25, *l* is changed to 3λ/5, 2λ/5 and λ/5, respectively.

V. CONCLSION

This paper has studied signal frequency spectrums under different distributions of metal wires based on traditional coaxial probe structures. It shows different filter performances of different distributions of metal wires. With TR technique, the super-resolution focusing performance is determined by the frequency point at the peak of signal frequency spectrum under random distribution of metal wires. The length and spacing of metal wires have important effects on the focusing performance and bandwidths. These results show that we can realize super-resolution characteristics applied in multi-antenna system by quantitative design of the micro-structures. Using the principles concluded from this paper to design super-resolution and ultra-wideband antenna will be the next direction in our research. Other micro-structured general design method different from thin metal wires also needs deep exploration.

REFERENCES

[1] R. Merlin, "Radiationless Elecrtonmagnetic Interference: Evanescent-Field Lenses and Perfect Focusing,' *Science,* vol. 317, pp. 927-929, August 2007.

[2] A. Grbic A, J. Lei J and R. Merlin, "Near-Field Plates: Subdiffraction Focusing with Patterned Surfaces," *Science,* vol. 320, pp. 511-513, April 2008.

[3] J. D. Rosny and M. Fink, "Overcoming the Diffraction Limit inWave Physics Using a Time-Reversal Mirror and a Novel Acoustic Sink," *Phys.Rev.Lett.,* vol. 89, pp. 124301, September 2002.

[4] G. Lerosey, et al. "Time Reversal of ElectromagneticWaves," *Phys. Rev. Lett.* Vol. 92, pp. 193904, May 2004.

[5] G. Lerosey, J. D. Rosny, A. Tourin and M. Fink, "Focusing Beyond the Diffraction Limit with Far-Field Time Reversal," *Science*, vol. 315, pp. 1120-1122, February 2007.

[6] G.-D. Ge, B.-Z. Wang, H.-Y. Huang and G. Zheng, "Super-resolution characteristics of time-reversed electromagnetic wave," *Acta Phys. Sin.* Vol. 58, 2009.

[7] G.-D. Ge, B.-Z. Wang, D. Wang, D.-S. Zhao, and S. Ding, "Subwavelength Array of Planar Monopoles With Complementary Split Rings Based on Far-Field Time Reversal," *IEEE Trans. Antennas Propag.* 9 vol. 59, pp.4345-4350, November 2011.

[8] G.-D. Ge, R. Zang, D. Wang, S. Ding and B.-Z. Wang, "Subwavelengtharray of planar antennas with defect oval rings based on far-field time reversal," *IET Electronics Letters*, vol. 47, pp. 16-17, August 2011.

[9] Z.-M. Zhang, B.-Z. Wang and G. -D. Ge, "A subwavelength antenna array design for time reversal communication," *Acta Phys. Sin*. vol. 61, pp.058402,2012.