Hybrid UV/MLFMA Analysis of Scattering by PEC Targets above a Lossy Half-Space

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Abstract **─** An efficient hybrid UV method and the multilevel fast multipole algorithm (MLFMA) is proposed for the analysis of scattering by arbitrary three-dimensional(3-D) perfect electric conductor (PEC) targets above a lossy half-space. The proposed method modifies the MLFMA based on the real-image representation of the half-space dyadic Green's function. Unlike the original MLFMA, the interaction matrix of the UV/MLFMA is split into the "near" terms, the "intermediate" terms, and the "far" terms. The "near" terms are handled via the method of moments (MoM), the "intermediate" terms are handled via the UV method, and the "far" terms are handled via the MLFMA. The error arising from the approximation to the half-space dyadic Green's function via the real-image representation in the "intermediate" terms can be avoided by using the UV matrix compression. The memory requirement and computational time of the "near" terms are also decreased significantly compared with the original MLFMA.

Index Terms **─** Half-space, multilevel UV method, MLFMA, and real-image.

I. INTRODUCTION

There is much interest in scattering from conducting objects situated above a lossy half-space, as there are many applications such as communications, target identification, and remote sensing. The MoM is the preferred method, since by using the integral equation (IE) and the half-space dyadic Green's functions, it only discretizes the metallic surface, which leads to a relatively small number of unknowns. The most challenging aspect of such a problem is the evaluation of the spatial domain half-space dyadic Green's functions which are expressed in terms of the Sommerfeld integrals (SI's). There is much research to solve the SI's, including the steepest-descent path (SDP) approach [1], and the discrete complex image method (DCIM) [2].

The implementation of the MoM requires $O(N^3)$ operations and $O(N^2)$ memory storage, where N is the number of unknowns. The size of the MoM matrix increases so rapidly that the computation will be intractable for a large number of unknowns. The difficulty can be overcome by use of Krylov iterative methods, and the required matrix-vector multiplication can be accelerated by the MLFMA [3-6]. The MLFMA is based on the addition theorem and the plane wave expansion, which are primarily in the context of the free space Green's function. It is not directly applicable to the half-space problem due to the complex form of the spatial domain Green's functions of half-space. In [7], a steepest-descent fast multipole method (SDFMM) was proposed for analysis of the quasi-planar structures whose transverse dimensions are much larger than the height. The SDFMM relies on a representation of the 3-D Green's functions to a steepest-descent integral coupled with a two-dimensional (2-D) fast multipole method. Therefore, it was applied to solve the problems concerning quasi-static structures such as scattering from the rough surface [8] and radiation from the microstrip antennas [9] etc efficiently. In [10-11], the MLFMA has been extended for general targets in the presence of a lossy half space. Since the "far" interactions between distant groups are less sensitive to accurate evaluation, the spatial domain Green's functions are approximated by both the direct-radiation term and the radiation term from a single real-image [10-11]. Then the computation of the "far" terms can be accelerated by the MLFMA. Due to the advantage of this technique, the MLFMA based on real-image approximation is extended to analyze the EM scattering by the arbitrary chiral objects above a lossy half-space [12].

The real-image representation of the Green's function is appropriate for expansion when the source and observation points are separated by a wavelength or more [13]. This determines the large minimum group size of the MLFMA, which leads to a low efficiency, as the minimum group size of the MLFMA at mid frequency in free space is around 0.2 wavelength. In [11], a higher order approximation for efficient evaluation of the half-space Green's function based on the large-argument approximation of Bessel function and Taylor series expansion is considered. The method can analyze targets in direct contact with the interface of a lossy half-space. However, the formula is complex and complicated to implement. In [14], the half-space dyadic Green's function is split into a term representing the "direct" radiation between source and observation points and a remaining "reflect" term accounting for interactions with the interface. The expansion coefficients of the "reflect" term are obtained by the sampling points in the source and observation groups. This approximation is easy to implement. However, the error of the approximation may be uncontrollable, since it is difficult to determine the appropriate sampling points.

The drawback of the MLFMA is its dependence on the integral kernel. For complex Green's functions, the application of the MLFMA is much more involved than in the free space. Thus, a large number of fast integral equation algebraic methods have already been developed. The matrix decomposition based methods such as IES^3 (ice cube) [15], hierarchical (H) matrices method [16], adaptive cross approximation (ACA) [17], and UV method [18] are kernel function independent. They are easy to be applied in the existing MoM code without a large change of the algorithms. However, the above methods are only efficient for moderate size problems, for large scale problems or at a high level of the tree structure in the algorithms the actual complexity is higher [19]. Therefore, in this paper, the multilevel UV method [16] is only used in the "intermediate" terms to overcome the difficulties for the approximation to the half-space Green's function and to avoid the higher computational complexity in the "far" terms. The computational complexity and memory requirement of the multilevel UV method is $O(rN\log N)$, where r is the typical (average) rank at the largest level [16, 18]. The half-space Green's function in the "intermediate" terms is evaluated via DCIM rigorously, and the multilevel UV method needs to only deal with the final low-ranked interaction matrix. Thus, the approximation error is controllable via the threshold in the UV matrix compression [16]. Since we focused on the analysis of the PEC targets by the hybrid UV/MLFMA, the MLFMA based on the real image approximation will not be described in this paper. The details can be found in references [8-10].

The remainder of the paper is organized as follows. Section II describes the essential algorithms for the analysis of the PEC targets above a lossy half-space. The half-space MoM formulation is described in Section II-A; the multilevel UV method based on the octree structure is described in Section II-B and the hybrid UV/MLFMA is described in Section II-C. Numerical results in Section III demonstrate the validity of the proposed method. Finally, a brief final conclusion is given in Section IV.

II. THEORY

A. Integral equation and half-space MoM formulation

For solving scattering by a PEC target located above a lossy half-space, the electric-field integral equation (EFIE) is utilized:

$$j\omega u_1 \int_s \left(\bar{\bar{\mathbf{I}}} + \frac{\nabla\nabla'}{k_1^2} \right) \bullet \bar{\bar{G}}^A \bullet \mathbf{J} dS' = \mathbf{E}^i(\mathbf{r}), \qquad (1)$$

where $\bar{\bar{G}}^A$ is the spatial domain dyadic Green's function and can be expressed as follows:

$$\bar{\bar{G}}^A = G_{xx}^A(\hat{x}\hat{x} + \hat{y}\hat{y}) + G_{zx}^A \hat{z}\hat{x} + G_{zy}^A \hat{z}\hat{y} + G_{zz}^A \hat{z}\hat{z}. \quad (2)$$

The spatial expressions of the above Green's functions are often expressed in terms of SI's. In this paper, DCIM combined with the two-level generalized-pencil of function method (GPOF) [20] is employed to evaluate efficiently the Greens' function for a half space.

B. Multilevel UV method

The multilevel UV method is a rank-based method. Generally, the interaction matrix is full-ranked when the observation groups are in the near field of the source group, while the interaction matrix between them is low-ranked when the observation groups are in the far field. Application of the UV decomposition to the low-ranked impedance matrix will result in significant memory and computational time savings. The classification of the interaction groups in this paper is based on the octree structure. A three level octree structure is demonstrated in Fig. 1.

Considering a 2-D target locating within a square region as an example (for the 3-D targets, it will be located within a cube, and the principle of classification of the interaction groups is the same as the 2-D). The square region is spitted into levels using the octree algorithm until there are some dozens of RWG functions in the minimum groups. For the observation block (block 1) at level-1, the impedance matrix can be decomposed into P sparse matrices, where P is the number of levels.

$$\mathbf{Z} = \mathbf{Z}_0 + \mathbf{Z}_1 + \cdots + \mathbf{Z}_{p\text{-}1}. \tag{3}$$

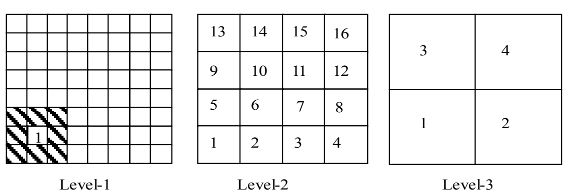

Fig. 1. A three level octree structure.

$\mathbf{Z}_0$ is the impedance matrix for the interactions of self and neighboring blocks (the hatched blocks and the self interaction block in Fig. 1) at level-1. The region of $\mathbf{Z}_0$ is defined as the near field of block 1 at level-1. $\mathbf{Z}_1$ and so forth are the impedance matrices for the interactions of the far field which is defined as the parent block's near field and the current block's far field. As shown in Fig. 1, for level-1, the far field of block 1 at level-1 is the region of blocks 5, 6, 2 at level-2 with the region of the near field of block-1 at level-1 excluded, since the block 1 at level-2 is the parent block of block 1 at level-1 and the blocks 5, 6, 2 are the neighbors of block 1 at level-2. Similarly, for level-2, the far field of block 1 at level-1 is the region of blocks 3, 4, 2 at level-3. Accordingly, all the interactions to block 1 at level-1 can be computed.

$\mathbf{Z}_0$ is full-ranked and is stored directly. For $\mathbf{Z}_1$ and so forth, the matrices are operated in two different ways according to their size when applying the UV method. When the size of the matrix is small, it will be computed directly and its rank is evaluated by singular value decomposition (SVD), after which the U and V matrices can be obtained. When the size of the matrix is large, column and row sampling according to rank estimates is performed and SVD on the sampled matrix is implemented instead. The $m \times n$ matrix is then decomposed into $\mathbf{U}_{(m\times r)}$ and $\mathbf{V}_{(r\times n)}$ matrices, which leads to significant time and memory savings when the matrix is low-ranked [21, 22]. It should be note that the process of the rank estimation spends no extra time compared with the process of the rank-revealing process of the ACA [17], since the **U** and **V** matrices are formed simultaneously within the SVD process.

C. The hybrid multilevel UV method and MLFMA

In this paper, the UV method is used to evaluate the "intermediate" terms to avoid the real-image representation of the half-space Green's function in this region. The UV/MLFMA method is similar to the multilevel UV method in that the impedance matrix is decomposed into P sparse matrices, where P is the number of levels

$$\mathbf{Z} = \mathbf{Z}_0 + \mathbf{Z}_1 + \cdots \mathbf{Z}_q + \cdots + \mathbf{Z}_{p\text{-}1}. \tag{4}$$

The hybrid method classifies the impedance matrix to the "near" terms, the "intermediate" terms, and the "far" terms as shown in Fig. 2. The "near" terms ($\mathbf{Z}_0$) are the same as described in section 2.2 and are evaluated by MoM. The "intermediate" terms are between the near terms and the half wavelength group size in the tree structure ($\mathbf{Z}_1$ to $\mathbf{Z}_q$), and are evaluated by the multilevel UV method. The half-space Green's functions in the above two terms are evaluated rigorously by the DCIM [2]. The "far" terms are the region where the group size is larger than half a wavelength ($\mathbf{Z}_{q+1}$ and so forth), and are evaluated by the MLFMA based on real-image approximation technique.

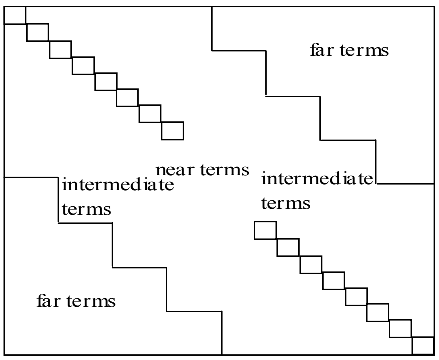

Fig. 2. The classification of the impedance matrix in the UV/MLFMA.

III. RESULTS AND DISCUSSIONS

Some numerical results of the PEC targets above a lossy half-space are shown in this section. The double floating point precision is used in the code to enhance the accuracy of the simulated results. All the numerical examples are computed on an Intel® CoreTM 2 with 3.0 GHz CPU's (the results are computed by only one processor) and 4 GB RAM. In this section the label "MoM" represents the simulated results by MoM rigorously, the "MLFMA" represents the simulated results by MLFMA based on the real image approximation, and the "UV/MLFMA" represents the simulated results by hybrid UV/MLFMA proposed in this paper. First, we analyze the scattering from a conducting sphere located at 0.7m above the lossy half-space characterized by $\varepsilon_{half} = (5.0, -0.2)$, $\mu_{half} = 1.0$ and $\sigma_{half} = 0$. The radius of the sphere is 0.5m and 2, 656 triangle patches are used to discretize its surface [14]. The incident and scattered directions are ($\theta^i = 0^\circ, \varphi^i = 0^\circ$) and ($0^\circ \le \theta^s \le 90^\circ, \varphi^s = 0^\circ$), respectively. The frequency of the incident plane wave is 300MHz. Figures 3 and 4 show the bistatic RCS computed by the MoM, the proposed method (one level UV method), and the MLFMA. The minimum group size for the octree structure is 0.5 λ_0 and 0.25 λ_0 , respectively. It can be found that when the minimum group size is 0.5 λ_0 , the results simulated by the MLFMA and the hybrid UV/MLFMA agree well with the results obtained by the MoM. But, when the minimum group size is minimized to 0.25 λ_0 , the results simulated by the hybrid UV/MLFMA agree better with the results obtained by the MoM than the results obtained by the MLFMA. Thus, the proposed method has a clear advantage of reducing the region of the "near" interactions that must be evaluated rigorously using the MoM. The total solution time for the MoM is 304.6 s, while the total solution time for the UV/MLFMA and MLFMA is 284.3 s and 97.3 s respectively. The proposed UV/MLFMA is more accurate than MLFMA when the minimum group size is smaller than 0.25 λ_0 .

Figure 5 shows the bistatic RCS of a PEC cylinder of height 3m and diameter 1m situated 20cm above Yuma soil of 10% water content. The metallic surface is discretized with 10, 404 triangle patches and the number of unknowns is 15, 606. The incident and scattered directions are ($\theta^i = 60^\circ, \varphi^i = 0^\circ$) and ($\theta^s = 60^\circ, -180^\circ \le \varphi^s \le 180^\circ$), respectively. It is found that the results computed by the proposed method (one level UV method and three level MLFMA) agree well with the results in [10]. The minimum group size of the UV/MLFMA is 0.25 λ_0 and the average number of RWG functions in the groups with minimum group size is 20. The "intermediate" term interactions are evaluated at the lowest level via the UV method and the "far" terms interactions are evaluated at level-2, level-3, and level-4 via the MLFMA. Figure 6 shows the comparison of the ranks and the column dimensions of the interaction matrices produced by the first group at the minimum level and its interaction groups. The number of the unknowns in the first group is 22. It is found that the dimensions of the interaction matrices are around 20 while the ranks are around 8 with the threshold of 10^{-4} in the matrix decomposition, which demonstrate the rank deficiency of the sub matrices in the proposed UV/MLFMA. By using the UV method in the "intermediate" terms, the size of the near field in the original MLFMA is decreased and its memory requirement is decreased from 226MB to 95MB, and the total solution time is decreased from 6929.1s to 4524.6 s.

Figures 7 and 8 show the memory requirement and CPU time respectively for the "near" terms of the MLFMA and the "near" and "intermediate" terms of the UV/MLFMA versus frequency for a tank model above a lossy half-space characterized by $\varepsilon_{half} = (5.0, -0.2)$, $\mu_{half} = 1.0$, and $\sigma_{half} = 0$. The length of the tank is 10.3m, the width is 3.3m, and the height is 2.3 m. The incident frequency of the plane wave is changed from 0.12GHz to 0.36GHz and the number of unknowns is changed from 21, 354 to 79, 008. It is found that significant memory requirements and CPU time are both saved in the "near" terms compared with the MLFMA for the proposed method in the simulated frequency band, which demonstrate the validity of the UV/MLFMA method. Figures 9 and 10 show the bistatic RCS for the VV- and HH-polarization of the tank model at the frequency 120 MHz. The incident and scattered directions are ($\theta^i = 0^\circ, \varphi^i = 0^\circ$) and ($\theta^s = 60^\circ, 0 \le \varphi^s \le 180^\circ$). Good agreement can be found.

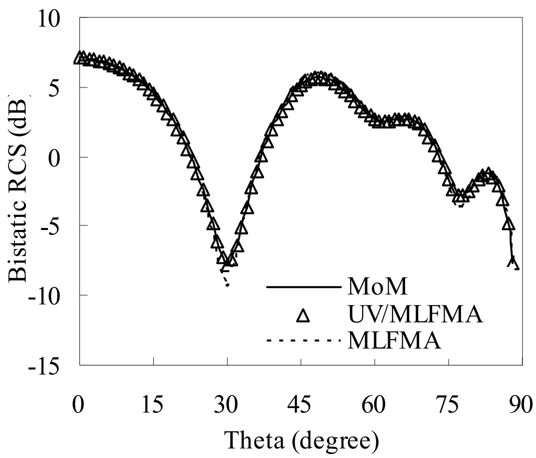

Fig. 3. Bistatic scattering cross section for VV-polarization of the conducting sphere at $\varphi = 0^\circ$. The minimum group size is 0.5 λ_0 for both the hybrid UV/MLFMA and the MLFMA based on real-image approximation.

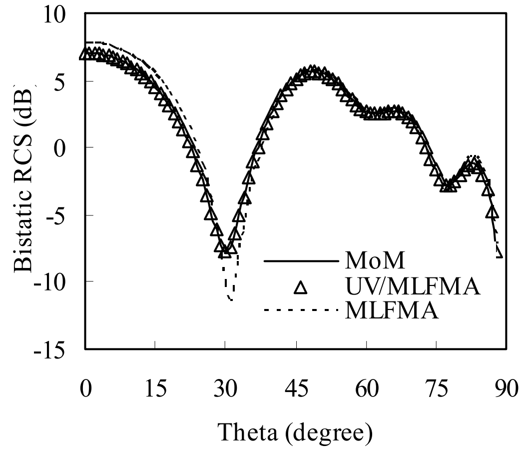

Fig. 4. Bistatic scattering cross section for VV-polarization of the conducting sphere at $\varphi = 0^\circ$. The minimum group size is 0.25 λ_0 for both the hybrid UV/MLFMA and the MLFMA based on real-image approximation.

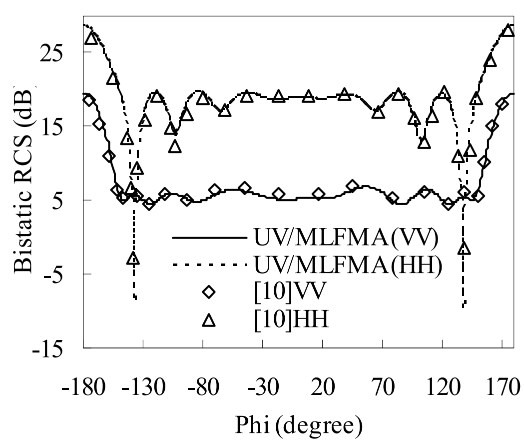

Fig. 5. Bistatic scattering cross section for VV- and HH-polarization of a PEC cylinder of height 3m and diameter 1m situated 0.2m above Yuma soil of 10% water content.

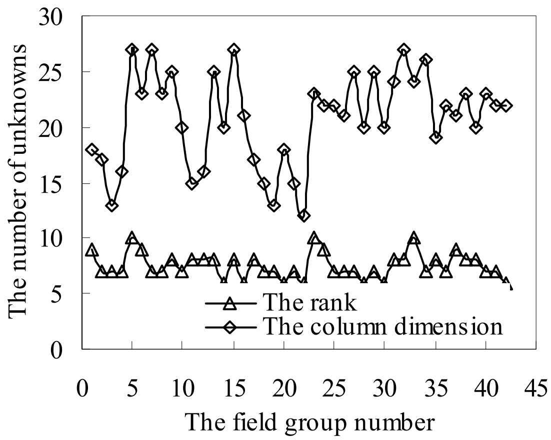

Fig. 6. The rank of the interaction matrix and the column dimensions of the first group at the minimum level. The horizontal axis represents the local group number of the observation groups in the "intermediate" field of the first group. And the vertical axis represents the number of unknowns in the observation groups, i.e. the column dimensions of the interaction sub-matrices. And the number of unknowns in the first group is 22.

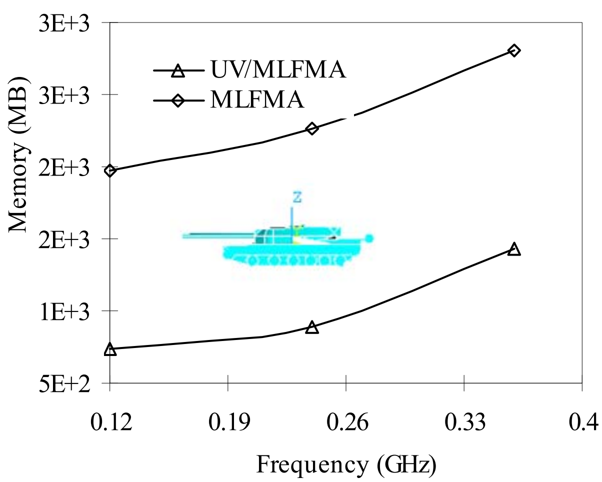

Fig. 7. Memory requirement for the "near" terms of the MLFMA and the "near" and "intermediate" terms of the UV/MLFMA versus the frequency for analysis of the tank above a lossy half-space.

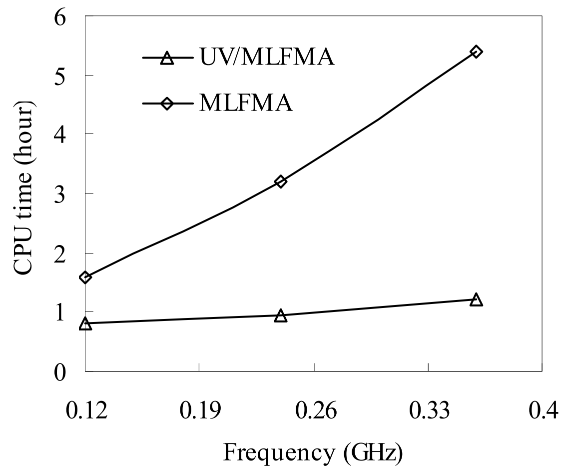

Fig. 8. CPU time for the "near" terms of the MLFMA and the "near" and "intermediate" terms of the UV/MLFMA versus the frequency for analysis of the tank above a lossy half-space.

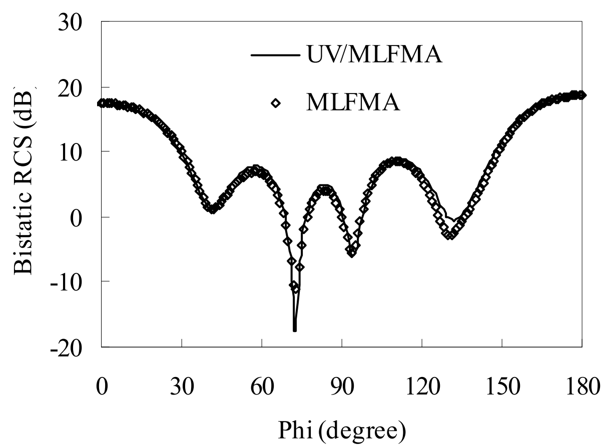

Fig. 9. The bistatic RCS for the VV-polarization of the tank model at the frequency 120 MHz.

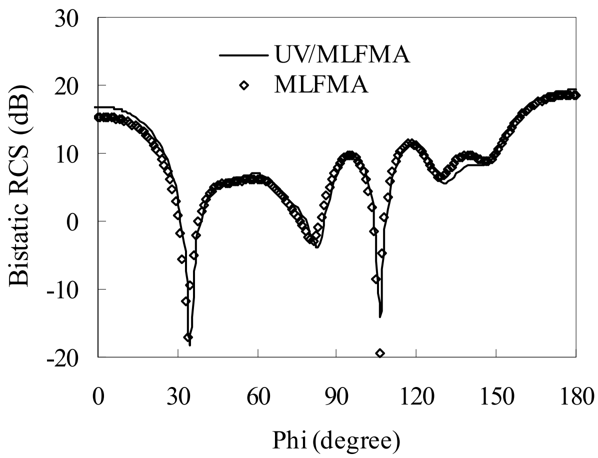

Fig. 10. The bistatic RCS for the HH-polarization of the tank model at the frequency 120 MHz.

IV. CONCLUSIONS

In this paper, a hybrid UV/MLFMA is proposed for the analysis of scattering by PEC targets above a lossy half-space. The multilevel UV method is applied to handle the interaction in the "intermediate" terms. The MLFMA is applied to handle the interaction in the "far" terms. By using the UV method in the "intermediate" terms, the error of the real-image approximation can be avoided and the size of the "near" terms of the original MLFMA is decreased. In this paper, we focused on analyzing PEC targets above a lossy half-space. For dielectric targets [11-12], the proposed method is also applicable with little change of the code.

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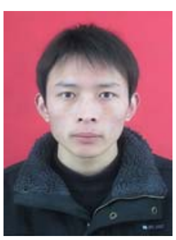

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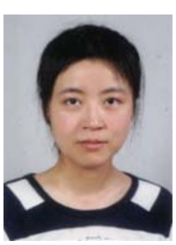

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