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Simulation Study on Dispersion Properties of As_2S_3 Three-Bridge Suspended-Core Fiber

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ABSTRACT In this paper, the chromatic dispersion of the As_2S_3 three-bridge suspended-core fiber (SCF) is numerically investigated. All the cross-section parameters, including the thickness of the bridges and the internal circle and external circle diameter of the air hole, have been considering in the simulation of the SCFs by means of the full-vectorial finite-element method in detail. Eighty three models with different structural parameters are established, and the changes of the chromatic dispersion and zero-dispersion wavelength (ZDW) of the fundamental mode in the wavelength ranging from 0.6 to 11.6 μm are evaluated. The relations between the dispersion and structural parameters are obtained by numerical simulations. Numerical results indicate that a proper design of the bridges and air holes can significantly change the dispersion properties of the SCF. A SCF with dual-ZDW (1.805 & 5.315 μm), highly nonlinearity (3.480683 $m^{-1}W^{-1}$), and flattened chromatic dispersion (<17.70133 ps/(km $\cdot$ nm)), which can be used to generate broadband supercontinuum, is obtained by optimizing the structural parameters.

INDEX TERMS Chalcogenide glass, dispersion, full-vectorial finite element method, suspended-core fibers.

I. INTRODUCTION

Suspended-core fiber (SCF) is a typical class of micro-structured fibers [1], which have attracted much interest due to their excellent optical properties, such as wavelength conversion, tunable dispersion, high nonlinearity, polarization maintenance, high birefringence, and soliton propagation [2]. Compared with other micro-structured fibers, SCF can provide a smaller effective mode area and a simpler method for tuning the dispersion [3]. Therefore, SCF has been widely used in fiber sensor [4], wavelength conversion [5] and supercontinuum (SC) generation [6], etc. Although the preparation of traditional silica fiber has been well established and its loss is very low, its transmission is limited to the visible or near-infrared region (NIR) of the spectrum from 0.4 to 2 μm [7]. In contrast, chalcogenide glass has great advantages over silica glass owing to their wide transmission window, low two-photon absorption [8], high nonlinear refractive index and high nonlinearity in NIR and mid-infrared region (MIR) [9]. With the specific composition of chalcogenide glass, its infrared transparency can exceed 10 μm and its Kerr nonlinearity can be 100-1000 times larger than that of silica glass at 1.55 μm [10]. However, the higher refractive index makes the material zero-dispersion wavelength (ZDW) shift to 4.5μm [11], which has an adverse impact on broadband SC generation. Hence, it is necessary to study the dispersion properties of chalcogenide SCF in NIR and MIR. Owing to good thermal stability and glass forming ability, As_2S_3 has become one of widely used chalcogenide glasses for drawing fiber [12]. Some theoretical and experimental results [13], [14] have been obtained by using As_2S_3 SCF to obtain SC in MIR.

The structure of the SCF has a pronounced influence on the dispersion characteristics. Recent studies, such as three holes [15], [16], four holes [17] and more holes [18], have obtained lots of achievements. M. El-Amraoui et al. [19] studied the dispersion of 3-hole SCF with different core size. They found the ZDW of the SCF was closed to 2 μm when the core size was around 2.1 μm. Weiqing Gao *et al.* [20] simulated the chromatic dispersion of the As_2S_3 MOF by finite difference time domain (FDTD), and the ZDW was

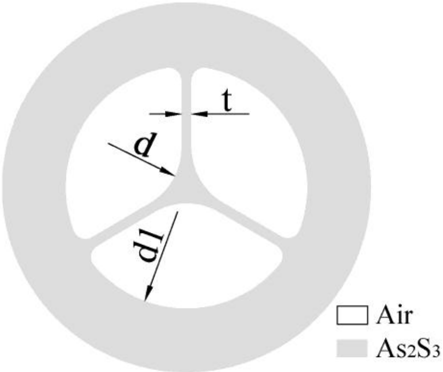

FIGURE 1. Designing views of the three-bridge SCF's geometrical formation.

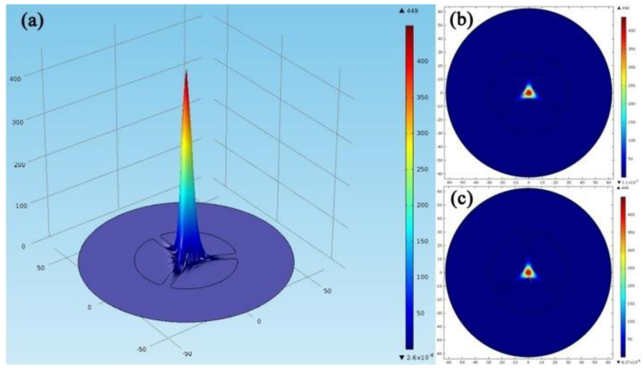

FIGURE 2. The simulated 3D plot of the fundamental mode (a) and intensity profile of (b) LP01−x and (c) LP01-y (t=5 μm, d1=60 μm, d=20 μm, λ =3 μm).

near 2.52 μm. M. Szpulak and Fevrier [21] studied the dispersion properties of SCF with small core by using finite element method (FEM). E. Coscelli et al. [22] investigated the factors that affect the dispersion characteristics in the case of different structures and parameters. However, a systematic research devoted to a thorough analysis of the effects of all the structural parameters on the dispersion properties has not yet been presented, to the best of our knowledge. In this paper, we simulate and analyze the As_2S_3 three-bridge SCF, which is the most simple structure, from 0.6 to 11.6 μm by using full-vector finite element method (FVFEM). The results can provide theoretical analysis for experimental research.

II. SCF STRUCTURES AND NUMERICAL MODEL

The cross-sectional view of the three-bridge is shown in Fig.1, where the grey part is As_2S_3 glass and the white one is the air hole. The guiding properties of the SCF are determined by three cross-section parameters, i.e., internal circle diameter of air hole (d), external circle diameter of air hole (d1) and thickness of bridges (t). The diameter of the SCF is fixed at 125 μm, values of t are set to be 1, 5 and 9 μm, d ranges from 0 to 120 μm and the values of d1 are set to be 20, 40, 60, 80 μm, respectively.

Using FVFEM, we find out the fundamental mode field distribution of the SCF, as shown in Fig.2, with the operating wavelength ranging from 0.6 to 11.6 μm. The effective refractive index (n_{eff}) of the SCF can also be obtained by taking into account the refractive index of As_2S_3 which is calculated according to the Sellmeier equation [23]:

$$n^2(\lambda) = 1 + \sum_{i=1}^{5} \frac{A_i\lambda^2}{\lambda^2 - L_i^2} \tag{1}$$

Here λ is the operating wavelength in μm. A_1-A_5, and $L_1^2 - L_5^2$ are the material constants. For the As_2S_3, the parameters are 1.8983678, 1.9222979, 0.8765134, 0.1188704, 0.9569903, 0.0225, 0.0625, 0.1225, 0.2025 and 750, respectively. The functions between n_{eff} and the operating wavelength can be determined by nonlinear function curve fitting and approximation as presented in our previous work [24]. Using the same fitting function, the system error caused by fitting can be reduced greatly, where it is most difficult to select the suitable fitting function and the parameters due to the wide range of wavelength (0.6-11.6 μm) and the high precision demanded (0.1 μm). The average sum of squared error and R-square of the fitting functions are $6.57e^{-5}$ and 0.99994, respectively. It can be observed that the fitting function we have obtained can reflect the relationships between n_{eff} and λ accurately. Finally, the values of chromatic dispersion (D) can be calculated by using the following equation [25]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{\partial^2 \mathrm{Re}[n_{eff}]}{\partial\lambda^2} \tag{2}$$

where $\mathrm{Re}[n_{eff}]$ is the real part of n_{eff}.

The effective mode are of fundamental mode can be obtained through the following expression:

$$A_{eff} = \frac{[\iint |E(x,y)|^2 dxdy]^2}{\iint |E(x,y)|^4 dxdy} \tag{3}$$

where E(x,y) is the electric field transverse distribution of the fundamental mode. In addition to n_{eff}, E(x,y) can be calculated by FVFEM.

The nonlinear coefficient is defined as [26]:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \tag{4}$$

where n_2 is the nonlinear refractive index of fiber material (As_2S_3 is estimated at 2.92×10^{-19} m^2/W [27]).

III. SIMULATION RESULTS AND DISCUSSION

If the core of SCF is large enough, the dispersion curve of SCF is consistent with the Sellmeier equation of bulk As_2S_3 glass, namely it increases with the increase of the wavelength, which is sharper in short wavelength than in long one. However, the rule may be broken when the core is smaller since the fundamental mode can't be confined in the core completely.

The three structural parameters (d1, d and t) of SCF are relatively independent, however, when d1 is smaller, the size of the air hole is limited, and the maximum value of d and t is limited for the same reason. Moreover, when d1 is fixed,

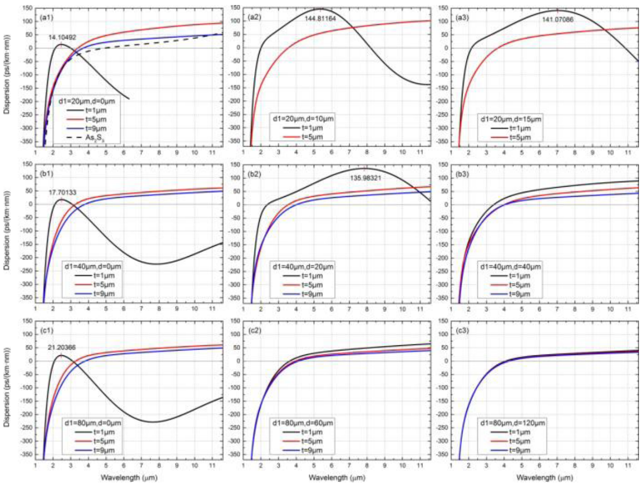

FIGURE 3. The effects of the thickness of bridges t on the dispersion of SCFs with (top to bottom) internal circle diameter of air hole d1=20 μm, 40 μm and 80 μm.

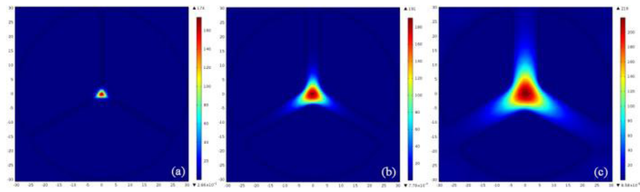

FIGURE 4. The distribution of fundamental mode magnetic field at λ = 4um for SCFs with d1=60 μm, d=10 μm and (a) t=1 μm, (b) t =5 μm, (c) t=9 μm.

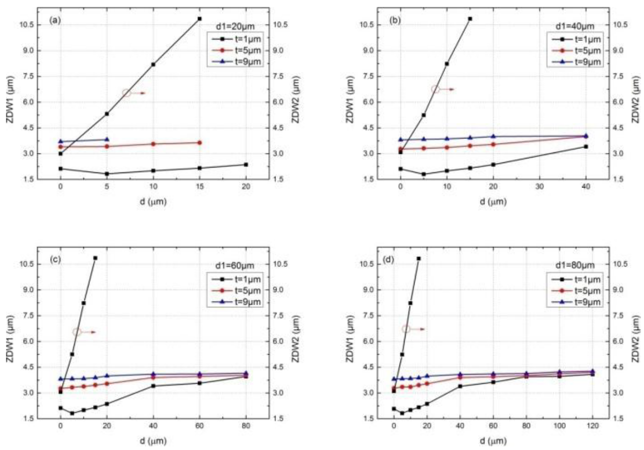

FIGURE 5. ZDW with different d, t and (a) d1=20 μm, (b) d1=40 μm, (c) d1=60 μm and (d) d1=80 μm.

the larger the value of d, the smaller the maximum value of t, and vice versa. In order to obtain the effect of the individual structural parameter on the dispersion of the proposed SCF, the other two parameters should be fixed during the simulation.

A. EFFECT OF THICKNESS OF BRIDGE ON DISPERSION

To study the effect of the bridges, the values of thickness are changed to be t=1 μm, 5 μm and 9 μm. The minimum value of t value is chosen in order to confine the fundamental mode field based on Gauss distribution into the core. The maximum value is selected considering the feeble influence of thicker bridges. Since the smaller d1 limits the structure of the air hole, the maximum value of t can only be 7 μm when d1=20 μm, d=10 μm & 15 μm, so the t values for the two structures are only 1 μm and 5 μm, and without 9 μm. As shown in Fig.3, the topmost graphs, labeled (a1)-(a3), show the results obtained for the SCF with d1=20 μm, and d=0, 10, 15 μm, respectively. Besides, the dispersion curve of bulk As_2S_3 glass is illustrated in Fig.3 (a1) [23]. Fig.3 (b1)-(b3) and (c1)-(c3), report D values for the SCF varying with d1=40, 80 μm, respectively. From Fig.3, we find that D is inversely proportional to t in general.

We can also see that the SCFs with larger t (>5 μm) have a similar slope of the dispersion curve with the pure bulk As_2S_3 glass, whose D values increase monotonously. By comparing the simulation results in Fig.3, it is obvious that the impact of the bridges becomes less significant with the increasing core radius. And for this reason, all the dispersion curves tend to converge. Therefore, the conclusions can be drawn that the dispersion curves turn to be flatter with the increase of t. It is worth noting that D varies greatly with wavelength for small cores, regardless of the variation of t, as shown by leftmost column of Fig.3 (a1)-(c1). This is possibly because the size of the core causes the fundamental mode field to be confined strictly by the air regions between the glass bridges as shown in Fig.4, thus alters the dispersion properties. In the case of narrower bridge, the fundamental mode is efficiently coupled into the suspended core and transmitting along the core only. On the contrary, more light is transmitted in the bridges with the increase of t value.

In addition to D, we also find that t has a great impact on the ZDW. As showed in Fig.5, the first ZDW (ZDW1) is 1.805 μm when t=1 μm and d=5 μm. Notice that wider t ($\geq$5 μm) causes the disappearance of the second ZDW (ZDW2) and a larger red-shift of the first ZDW. Moreover, the simulation results show that t causes a significant change in the value of ZDW in the case of small d. However, the effect of t on ZDW will decrease with the increase of d. When d reaches its maximum value, the biggest impact on dispersion is not more than 0.75 ps/(km·nm).

B. EFFECT OF INTERNAL CIRCLE DIAMETER OF AIR HOLE ON DISPERSION

Fig.6 shows that the dispersion curves of SCF versus wavelength tend to be flat with the increase of d, regardless of t and d1 values. Fig.6 also tells that generally the value of the dispersion decreases with the increase of d, though it is not obvious, especially for the SCF with larger core. On the contrary, the effect of d on dispersion is pronounced when t is very small, due to the weaker guided mode field confinement in the core. The high air-filling fraction, increasing with the decrease of d, makes the fundamental mode

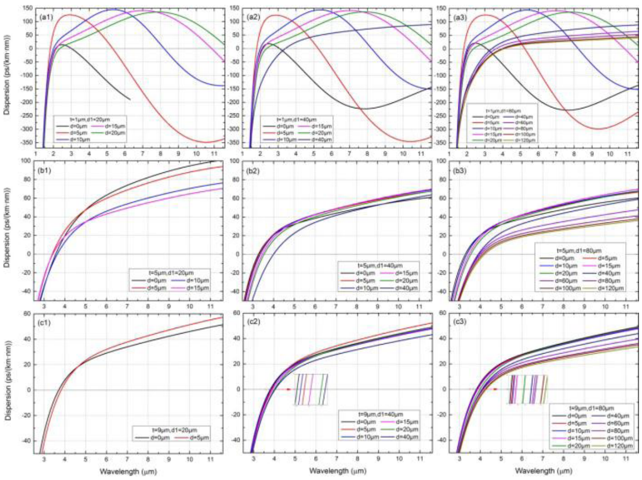

FIGURE 6. The effects of internal circle diameter of air hole d on the dispersion of SCFs with (top to bottom) thickness of bridges t=1 μm, 5 μm and 9 μm.

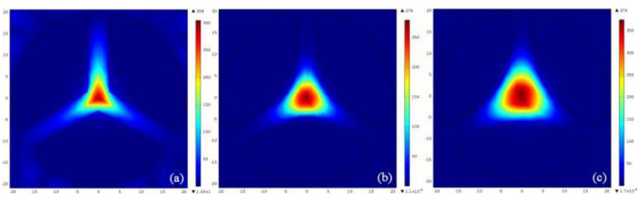

FIGURE 7. The distribution of fundamental mode magnetic field at $\lambda = 5$ μm for SCFs with t=5 μm, d1=40 μm and (a) d=0 μm, (b) d=20 μm, (c) d=40 μm.

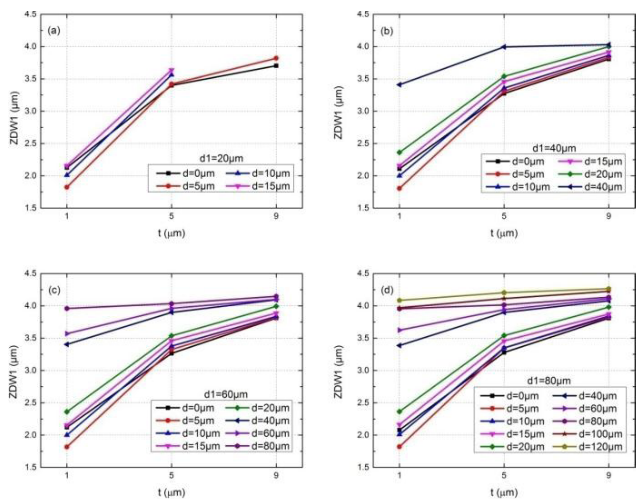

FIGURE 8. The first ZDW with different t, d and (a) d1=20 μm, (b) d1=40 μm, (c) d1=60 μm and (d) d1=80 μm.

field restricted strongly in the core, which is strictly related to the dispersion curve behavior. In the case of d is very small, in particular equal to 0, the fundamental mode field is subjected to the strong extrusion of the internal circles of the air holes. The shape of the field is deformed by this reason, even from the circle to the triangle, as shown in Fig.7.

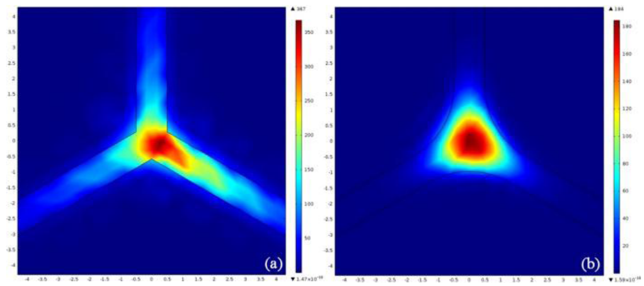

FIGURE 9. The distribution of fundamental mode magnetic field at $\lambda = 2$ μm for SCFs with t=1 μm, d1=80 μm and (a) d=0 μm, (b) d=5 μm.

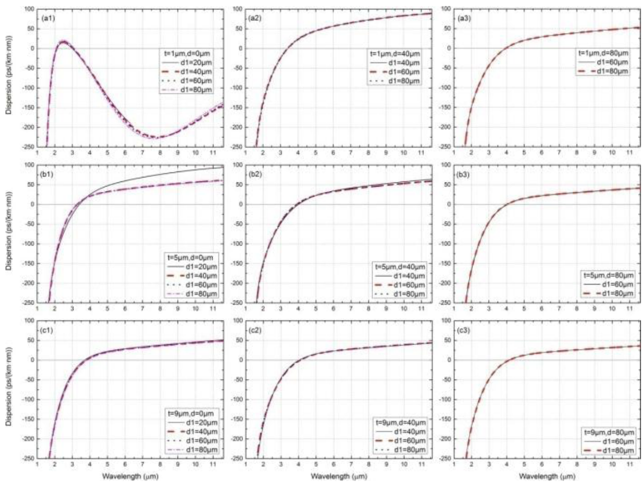

FIGURE 10. The effects of external circle diameter of air hole d1 on the dispersion of SCFs with (top to bottom) thickness of bridges t=1 μm, 5 μm and 9 μm.

It is also important to underline that the ZDW has red-shift with the increase of d, as shown in Fig.8. Notice that the first ZDW red-shifts rapidly when d changes from 20μm to 40μm, regardless of t and d1. In particular, the second ZDW will disappear with the red shift. Fig.5 also demonstrates that the SCFs with t=1 μm and d $\leq$ 15 μm, regardless of d1, always have dual-ZDW. If d1 is very small, such as 20 μm, the effect of the increasing d on ZDW is not evident particularly. On the contrary, the influence becomes more significant when the value d increases and the value t decreases. Finally, those curves of the first ZDWs are approaching very close. In particular, when d reaches the maximum value of each structure, the variation of the first ZDW is almost negligible. However, there is an exception to this rule. The internal boundary of the air hole is discontinuous as a result of d=0 μm, as shown in Fig.9, so tremendous changes have taken place in the shape of the fundamental mode field. As shown in Fig.6(a1), the cut-off wavelength that is about 6.3 μm has been simulated under the condition of t=1 μm. Numerical results show that, no matter how much d1 is, the first ZDW is always near 2.1 μm, and the second ZDW is always proportional to d. Besides, the first and second ZDW red-shifts respectively from 1.82 μm to 4.085 μm and 3.105 μm to 10.824 μm by adjusting d when t=1 μm.

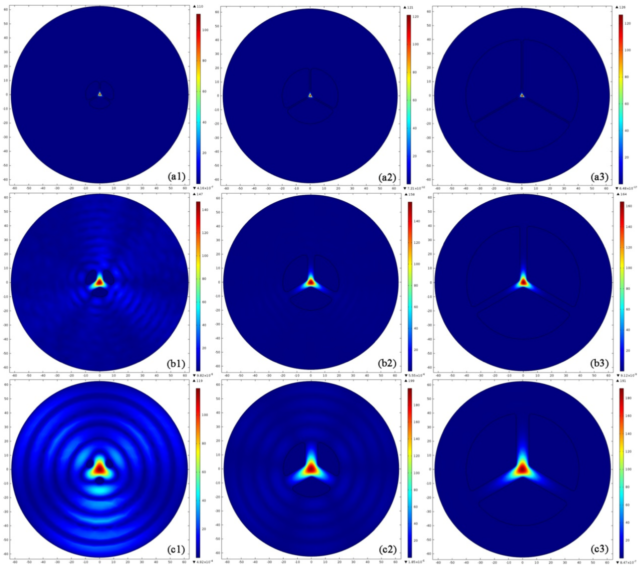

FIGURE 11. **The distribution of fundamental mode magnetic field at $\lambda = 3\ \mu$m for SCFs with (top to bottom) thickness of bridges t=1 μm, 5 μm, 9 μm, and (left to right) internal circle diameter of air hole (a) d1=20 μm, (b) d1=40 μm and (c) d1= 80 μm.**

C. EFFECT OF EXTERNAL CIRCLE DIAMETER OF AIR HOLE ON DISPERSION

Fig.10 shows that the effect of d1 on D and ZDW is not great especially in the larger core. This is mainly because the mode field of SCF is determined by the structure of the fiber core, rather than the air-filling rate. As shown in Fig.11, once the fundamental mode field is established, the effective mode area and the effective refractive index of the SCF have little change, regardless of d1. These are the reasons why the fluctuation of the dispersion and the shift of ZDW are not very obvious. Nevertheless, the air-filling fraction will play an effective role in the property of modes and radial distribution of the field since the fundamental mode field has been completely limited, as shown in Fig.11.

IV. CONCLUSIONS

In this work, the effect of structural parameters (thickness of bridges t, internal circle diameter of air hole d and external circle diameter of air hole d1) of As_2S_3 three-bridge SCF on chromatic dispersion properties has been systematically studied within the wavelength range from 0.6 to 11.6 μm by using FVFEM. The investigated results indicate that the three parameters are all inversely proportional to the dispersion in general. The influence of the two key parameters t and d on the value of dispersion D and zero-dispersion wavelength ZDW is much greater than d1, which becomes less significant with increasing core diameter. Although the dispersion is more flatter with the increase of t and d1, the two ZDW red-shifts rapidly, and the second ZDW that is very important to the SC generation is disappearing gradually. When t=1 μm, d=5 μm and d1=40 μm, the minimum first ZDW is near 1.805 μm. By adjusting d from 0 to 120 μm, the first ZDW red shifts from 1.82 μm to 4.085 μm (about 2.265 μm) and the second shifts from 3.105 μm to 10.824 μm (about 7.719 μm).

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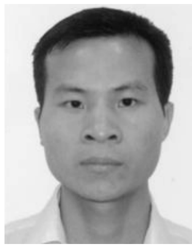

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