Advantages of photon scanning tunneling microscope combined with atomic force microscope

Jian Zhang (章 健), Yinli Li (李银丽), Gaoshu Jian (简国树), Ping Zhou (周 平), and Shifa Wu (吴世法)

Near-Field Optics and Nano-Technology Institute, Department of Physics, Dalian University of Technology, Dalian 116024

A new nano-meter scale resolution optical imaging mode and functional prototype of photon scanning tunneling microscope (PSTM) combined with atomic force microscope (AFM) named as AF/PSTM are introduced, and the advantages of AF/PSTM are discussed. Two separated optical images (refractive index image and transmissivity image) and two AFM images (topography image and phase image) of sample can be obtained during AF/PSTM's once scanning. AF/PSTM is applicable to all transmission samples in many fields, such as nano-biology, medicine, nano-optics, nano-industry, nano-science and technology, high-education and so on.

OCIS codes: 170.5810, 180.5810, 240.7040, 110.0110, 180.0180, 170.0110.

Since scanning tunneling microscope (STM) was invented by Binning *et al.*[1] in 1982, atomic force microscope (AFM) was developed successively by Bohl *et al*[2−5]. The aperture scanning near-field optical microscope (A-SNOM) has been developed in the middle of 80s last century. Ferrel *et al* won the first PSTM patent in USA[6] in 1991. The first PSTM system in China has developed in 1993, This first PSTM's transverse resolution is better than 10 nm and longitudinal resolution is better than 1 nm[7,8]. The image resolution of PSTM is better than that of A-SNOM[9,10], and the image contrast and optical system efficiency are much better than that of A-SNOM respectively. Further more, only PSTM can obtain the refractive index image of sample[8−13]. The previous PSTM system (with only one beam for dissymmetry laser beam illuminating sample) requests rigorous leveling sample surface to avoid artifact image caused by dissymmetry illumination mixed to the PSTM image[11]. In general, not only all the previous PSTM system (with single laser beam illuminating) imaging have the optical artifact false image, but also the optical image and topography image of sample and sometimes with artifact false image are mixed with each other and cannot be separated. The application and industrialization of previous PSTM is limited for above reasons. Wu[12−14] provide the method to eliminate the artifact false image in PSTM by use of π-symmetry incoherent bi-laser beams to illuminate sample. Based on numerical simulation[15,16] and experimentation research[17], this method can be confirmed effectively in reducing artifact false image in PSTM[16−18]. The same method in restraining PSTM artifact false image was also put forward by Vannier *et al*[18], and its numerical simulation was reported and the prototype of AF/PSTM was developed by Wu *et al*[19−21]. The principle of bi-functional optical fiber tip resonance modulation imaging mode AF/PSTM is introduced and the advantages of AF/PSTM are discussed in this paper.

AF/PSTM system is integrated both principles of PSTM and AFM[20], and the sample's PSTM optical images (refractive index and transmissivity image) and AFM images (topography image and phase image) can be obtained in once scanning. The kernel part of AF/PSTM system is the bi-functional bent optical fiber tip element (see Fig. 1), which has functions of both PSTM tip and AFM tip.

Under the constant amplitude scanning imaging mode, the four AF/PSTM images will be obtained during once scanning: the sample refractive index image $n_1(x,y)$, transmissivity image $T(x,y)$, the sample topography image $\Delta Z_0(x,y)$, and phase image $\Delta P(x,y)$ or topography gradient image $\Delta Z_0'(x,y)$.

AFM system will collect the feedback micro-modulation value of the sample's Z-direction as the sample topology image $\Delta Z_0(x,y)$ and will collect phase image $\Delta P(x,y)$. PMT system will collect photon tunneling information (see Fig. 2, for every one image element, where $I_{\max}$ (Z=0) and $I_{\min}$(Z=2A) is the peak value and the valley value of PSTM photon tunneling information respectively, the peak to peak difference is $\Delta I = I_{\max} - I_{\min}$, the average values is $\bar{I} = (I_{\max} + I_{\min})/2$. According to the formula of evanescent wave of sample near-field, the refractive index $n_1(x,y)$ and tranmissivity

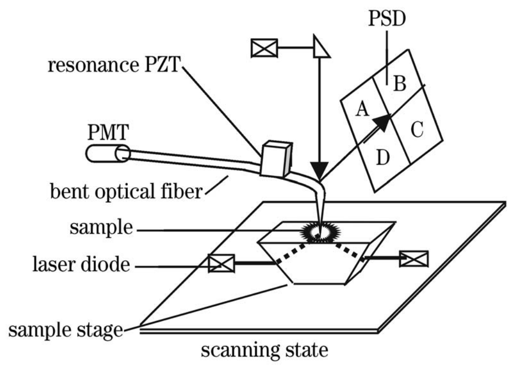

Fig. 1. The bi-functional bent optical fiber tip set.

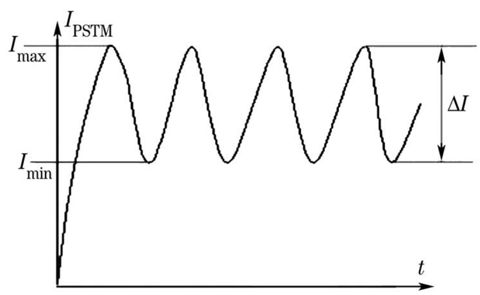

Fig. 2. The wave of information of PSTM.

$T(x, y)$ of sample can be nearly expressed as[14,19]

$$n_1(x,y) \propto -[\Delta I(x,y)/\bar{I}(x,y)]^2, \quad (1)$$

$$T(x,y) \propto I_{\max}(x,y). \quad (2)$$

The developed AF/PSTM prototype is shown in Fig.3, the AF/PSTM main microscope is set below a binocular stereomicroscope with conjugated imaging planes. Sample is put on the sample stage of total internal reflection prism, which is set on PZT 3D scanning tube. PMT output photon-tunneling information will be send to PSTM-unit.

The advantages of AF/PSTM are described as follows. First, Separating the refractive index image and tranmissivity image from topography image. Based on the dual-functional vertically resonance fiber tip and using the constant amplitude scanning mode, not only we can separate the near-field optical information from the topography information of sample but also separate the refractive index image $n_1(x,y)$ from tranmissivity $T(x,y)$ of sample. Figure 4 is the AF/PSTM images of 1 kpl/mm holographic grating, the four images are different from each other. A white speck in AFM topography obviously displaying a foreign body, which is under the emulsion film because it cannot be seen in the phase imaging. The refractive index image PSTM $n_1(x, y)$ can shows Ag particles depositing in emulsion film to form a grating, but can not see the foreign body in the emulsion film. Where the foreign body is? It can influence transmissivity image PSTM $T(x, y)$, so it may be in the emulsion film or under the emulsion film. But the refractive index image has fully grating image, which do not be influenced by the foreign body. The foreign body is unique under the emulsion film and on the substrate of the grating. It could not be explained only with AFM or with PSTM. This shows the special function of AF/PSTM.

Second, the resolution of PSTM is superior to that of A-SNOM. It is one of the theoretical progresses of near-field optical microscopy that Courjon and Bainier first explain the connection between Heisenberg uncertainty principle and Reyleigh criterion[22]. In order to realize super-resolution, the dimension of the spatial uncertainty of emitting photons as the carrier of sample information and the effective dimension of detecting tip must be smaller than that of Reyleigh diffraction limit, and the detected photons from sample must take the form of evanescent wave. Those are the determinants of the super-resolution optical imaging[22]. As we know the

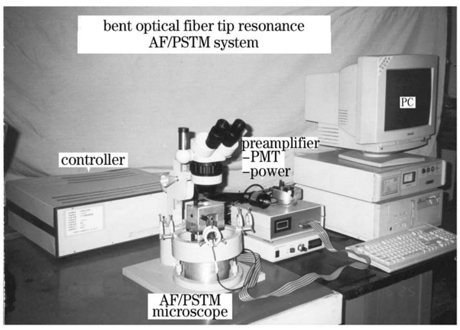

Fig. 3. Photo of AF/PSTM.

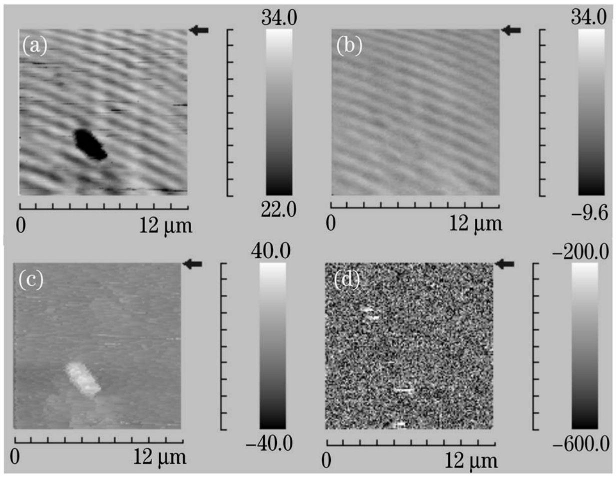

Fig. 4. 1 kpl/mm holographic grating AF/PSTM images. (a) PSTM $T(x,y)$, (b) PSTM $n_1(x, y)$, (c) AFM topography, (d) AFM phase imaging.

efficient dimension of commercial A-SNOM tip around 60–100 nm because of it must be covered with metal, but the efficient dimension of PSTM tip (which is bare) has reached around 10–20 nm. An amount of super-resolution PSTM images have been got in 1993 with our first PSTM system[7−9].

We have got the FWHM of line-spread-function (LSF) about 2.8 nm in our PSTM experiment[11]. Figure 5(a) shows a PSTM image of resin-film, its average of 15 profiles (in the region between two arrows) is shown in Fig. 5(b), and the LSF(line spread function) of PSTM imaging Fig. 5(c) shows FWHM about 2.8 nm.

Third, the imaging with P-polarization evanescent wave is superior to that of S-polarization: Only the evanescent wave may carry the super-resolution information of sample, and the P-polarization evanescent wave imaging may much better than that of S-polarization evanescent wave. We will show a comparable simulation results of PSTM between P- and S-polarization

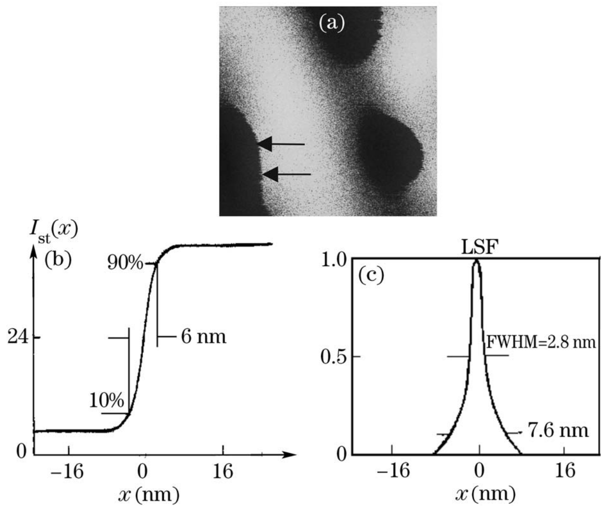

Fig. 5.(a) PSTM image of resin film (640 nm×640 nm), (b) the average of 15 profiles $I_{st}(x)$, (c) LSF of PSTM imaging.

evanescent waves, see Fig. 5, which shows two constant high mode (CHM, 10 nm above surface of sample) PSTM images of "PSTM".

Why does the P-polarization wave letters "PSTM" image in Fig. 5 is much better than that of the S-polarization wave letters, the reason is that the P-polarization evanescent wave is a longitudinal wave, its longitudinal electronic field influence laterally area is much smaller than that of S-polarization evanescent wave belongs to lateral polarization wave. The lateral polarization wave's laterally electronic field influence the lateral area at polarization-direction is larger than that of the vertical direction to polarization, seeing S-polarization wave letters "PSTM" image, the polarization-direction is parallel to y axial of Fig. 6.

A set of symmetric beam illumination device for PSTM can effectively decrease optical spurious image, the device limits the spurious effects due to non-isotropic illumination.

Fourth, AF/PSTM is applicable especially to nano-biology. AF/PSTM is applicable to all transmission sample, especially in biology and medicine, the reasons are as follows:

1) The potential resolution limit of AF/PSTM is approach to that of super-high resolution TEM in biology sample, which is about 1–3 nm, because the super-slice limit is 10–20 nm for bio-tissue in TEM imaging.

2) The bi-functional bent optical fiber tip vertically tapping does not destroy bio-sample and tip itself.

3) The bio-aliveness of sample can be kept within AF/PSTM imaging.

4) AF/PSTM imaging under high-humidity or liquid environment is possible after some improvement.

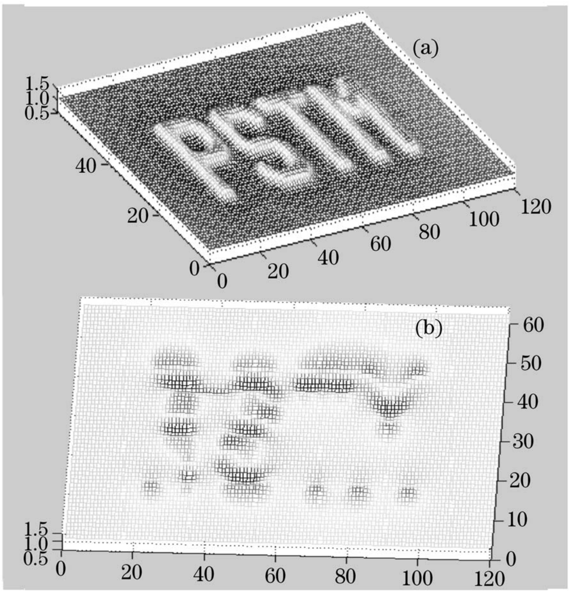

Fig. 6. Simulation results of CH-mode (10 nm) PSTM imaging. (a) P-polarization wave image, (b) S-polarization wave image.

5) The refractive index imaging needs no stain for imaging.

S. Wu is the author to whom the correspondence should be address (e-mail:wsf@dlut.edu.cn).

References

1. G. Binnig. and H. Rohrer, Helv. Phys. Acta. **55,** 726 (1982).
2. D. Pohl and D. Courjon (eds.), *Near-Field Optics* (NATO AST Series E242) (Kluwer, Dordrecht,1983).
3. D. Courjon and C. Bainier, Rep. Prog. Phys. **57,** 989 (1984).
4. C. Girard and A. Dereux, Rep. Prog. Phys. **59,** 657 (1986).
5. E. Betzig, P. L. Finn, and J. S. Weiner, Appl. Phys. Lett. **60,** 2484 (1982).
6. T. M. Ferrel, K. J. Warmarck, and R. C. Reddick, "Photon Scanning Tunneling Microscopy", Int. CI5: G01B11/24. United States, Patent number: 5,018,865 (1991).
7. J. Yao, S. Wu, S. Gao, N. Guo, G. Shang, D. Xia, J. He, S. Chu, and C. Li, Electronic Microscope Transaction (in Chinese) **16,** 222 (1997).
8. S. Wu, J. Yao, G. Jian, N. Guo, Acta Opt. Sin. (in Chinese) **18,** 191 (1998).
9. S. Wu, G. Jian, S. Pan, and Y. Wang, in *Proceeding of 2nd Asia-Pacific Workshop on Near-Field Optics*, 79 (2000).
10. S. Wu, S. Pan, and G. Jian, Proc. SPIE **4098,** 125 (2000).
11. S. Wu, Scanning **17,** 18 (1995).
12. S. Wu, "The Separating Method of Photon Tunneling Scanning Image" (in Chinese), Chinese Patent ZL93 1 04111.2 (1999).
13. S. Wu, "The Separating Method and Device of Photon Tunneling Scanning Image", Priority Japanese Patent, 3339658 (2002).
14. S. Wu, "The Separating Method of Image of Atomic Force / Photon Scanning Tunneling Microscope"(in Chinese) Chinese Patent, ZL96 1 11979.9 (2002).
15. G. Jian, S. Pan, and Y. Wang, Electronic Microscopy Transaction (in Chinese) **18,** 13 (1999).
16. X. Wang, G. Jian, W. Liu, S. Pan, and S. Wu, in *Proceedings of 2nd Asia-Pacific Workshop on Near-Field Optics* 123 (2000).
17. S. Wu, G. Jian, and S. Pan, Proc. SPIE **3467,** 34 (1998).
18. C. Vannier, C. Bainier, Opt. Commun. **175,** 83 (2000).
19. S. Wu, S. Pan, J. Zhang, W. Liu, and J. Wang, Chin. Eng. Sci. **3,** 33 (2001).
20. S. Wu, J. Zhang, Y. Huang, Y. Li, W. Sun, and S. Pan, in *Proceedings of 2002 Annual Meeting of China Optics* **1,** 245(2002).
21. S. Pan, S. Wu, W. Sun, Y. Li, Y. Zhang, and G. Jian, in *Proceedings of 2002 Annual Meeting of China Optics* **1,** 240.
22. S. Wu, G. Jian, and S. Pan. Acta Photon. Sin. (in Chinese) **27,** 52 (1998)