Design and Optimization of Tapered Optical Fiber Probes for SERS Utilizing FDTD Method

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Received: 6 April 2022 / Accepted: 30 August 2022 / Published online: 15 September 2022
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Abstract
In this work, we report a strategy of Ag nanoparticle (Ag NP)-coated tapered optical fiber probes by finite difference time domain (FDTD) simulations. Investigation shows that the fiber-tip decorated Ag NPs has excellent electric field enhancement and confinement of light capabilities. Moreover, we demonstrate the effect of key parameters such as tip radius, conical angle, Ag NP size, and gaps between them on the field enhanced utilizing typical excitation wavelengths of 532, 633, and 785 nm. To further improve the electrical field effect, a noble metal substrate is introduced below the tip apex, which exhibits a higher field enhancement generated by tip-substrate coupling. The presence of the Au substrate does not lead to a significant change in the plasma characteristic peak of the probes at 490 nm. This study provides a useful reference for the fabrication of tapered optical fiber with plasmonic nanostructures and the design of robust tapered fiber-optic Raman sensors.

Keywords Tapered optical fiber · Ag NPs · FDTD simulation · Surface enhanced Raman scattering

Introduction
Sensitive optical fiber, as a powerful sensing technology, can be used in various applications, such as food safety, environmental, chemical, and biological sensing [1–3]. With the development of optical fiber technology, several studies combining surface-enhanced Raman scattering (SERS) with optical fiber to develop promising LSPR and SERS fiber probes have been reported [4, 5]. Compared with traditional SERS substrates, the fiber probes can not only realize large SERS enhancement but also provide an ideal platform for remote measurements and make in situ sensing possible [6–8]. As a result, the development of excellent SERS-based sensors has received wide attention in both industry and academia.

The key principle of the SERS fiber probes is the preparation of nano-structures at the end of the excitation fiber and modified SERS-active sensing layers such as noble metal nanoparticles and metal films. In addition, it is a known fact that the detection sensitivity of the probes is related to the local electric field enhancement generated by the plasma micro/nanostructure, in which the fiber probe can be delivered both the excitation light to the sample and the backscattered SERS signal to the Raman spectrometer. To date, there are various types of optical fiber structures serving developed as SERS fiber probes [9–13]. Although many fibers probe have been prepared and excellent Raman signals obtained, the practical applications of SERS are still limited, especially the knowledge of electromagnetic field enhancement mechanism [14, 15]. The current theoretical analysis method for SERS fiber probes is numerical analysis. This a powerful tool for analyzing electromagnetic field enhancement. To obtain high Raman enhancement, several performance improvement methods are usually combined with numerical simulations to optimize the geometry of the fiber probes and shearing of the SERS-active layer. Tang et al. [16] successfully fabricated spherical SERS fiber probes and coated the spherical fiber tips with Ag NPs. The higher SERS enhancement factor can be obtained by optimizing the diameter of the fiber spheres. A grid nanostructured SERS fiber sensor using the numerical simulation analysis has been presented and shown a double characteristic peak, which offers the possibility to realize plasmon resonance excitation mode [17]. In addition, the field enhancement properties and parameter optimization of tapered fiber SERS probes coated with Au NPs on their tip have been also investigated using the FDTD method [18]. The FDTD methods are also applied.
to the design of gas fiber probes to analyze the electric field distribution, polarization properties, and the interpretation of the physical mechanisms [19, 20]. The three-dimensional computation numerical can be used to pinpoint the location of hot spots on the probe surface and to analyze the ultrashort pulse propagation of the tapered optical fiber probe [21]. Both the above experimental and theoretical studies show that the SERS sensitivity of the probe is strongly influenced by fiber geometry and the NPs. At present, various methods are used to fabricate SERS fiber probes with randomly undefined shapes and sizes [22, 23], which are mainly due to the effect of fiber size, poor operability, and controllability of the fabrication procedures. Therefore, it is necessary to combine numerical modeling simulation to design probes to get further insights into the general importance of identified relationships, reduce production cost and improve the production efficiency of the probes. Among them, tapered fiber probes have a larger specific surface area than other shape probes and show many advantages of the high light transmission efficiency and large interaction area for the excitation light and SERS signal [24].

In this study, FDTD simulations are used to design and numerically simulate the tapered fiber probes. The results show that the field enhancement properties of the fiber tip-modified Ag NPs are significantly improved. Moreover, the relevant parameters, including tip radius, cone angles, Ag NPs size, and gaps between them, are optimized. Finally, the electric field strength can be further improved by introducing a noble metal substrate below the fiber tip. This study provides a realistic theoretical reference for the application study of tapered fiber probes in Raman spectroscopy.

**Propose Structure Description and FDTD Simulation**

Firstly, we designed a tapered fiber probe with Ag NPs modified on the surface of the fiber tip. A default design parameter tapered angle \((\theta=41.2^\circ)\), tip radius (50 nm), Ag NPs radius (50 nm), the gap between Ag NPs (5 nm), and the gap between the Ag NPs and fiber tip surface of 1 nm were provided [25]. Subsequently, the electromagnetic field simulations were performed using the FDTD method via a commercial software package (Lumerical Solutions, Inc.) to investigate the local electric field enhancement and SERS enhancement factor (EF). The base solver directly solves Maxwell’s equations in both time and space on a spatial grid, where there are no any simplifying approximations, making the analysis far more accurate. To improve simulation efficiency, trade-off memory requirements, and simulation time for an ordinary computer, a 2D simulation model of tapered fiber coated with Ag NPs was designed on the \(x-y\) plane, as shown in Fig. 1. This appropriate simplified 2D scattering problem will not reduce the accuracy of the results [26]. Gaussian Beam was used as excitation light with the same total width as the excitation boundary, and the excitation field amplitude \((E_0)\) was set to be 1 V/m. The vector \(K\) was defined to propagate in the \(y\) direction with a polarization mode either in the \(x\)- or \(z\)-directions (p and s polarizations, respectively). Perfectly matched layers (PML) were used in the \(x-y\) directions as the boundary conditions to truncate computational regions. According to the Drude model, the dielectric constant \(\varepsilon_m\) of Au in the visible and near-IR can be written as [27].

\[
\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\omega\omega_c}
\]

where \(\varepsilon_\infty\) is the angular frequency of incident light, \(\omega_p\) is the plasma frequency of Ag which is the frequency of the oscillations of electron density in the metal, \(\omega_c\) stands for collision frequency, which corresponds to the damping of electron density oscillations due to collisions among the electrons, and the data are given by Johnson and Christy [28]. As for calculation capability, the mesh spacing is fixed at \(dx=0.001\ \mu m\) and \(dy=0.001\ \mu m\) to ensure accuracy, sufficiency, and stability for this study.

![Fig. 1 The 2D diagram of the simulation model of tapered optical fiber coated Ag NPs on x-y plane](image)
Results and Discussion

Uncoated Tapered Optical Fiber

Before studying other parameters, the optical propagation characteristic in a tapered optical fiber was analyzed by two different polarization directions. The incident light is perpendicular to the excitation boundary, the shape of the fiber tip is determined by a tip radius of 50 nm, excitation boundary of the radius width of 0.8 μm, and cone angle of 41.2°. Figure 2 shows the spatial field distribution of the fiber tip calculated by 2D-FDTD simulations. For two different polarizations: Fig. 2a is p-polarized, and Fig. 2b is s-polarized light excited by 785 nm, respectively. The color map represents the maximum electric field value. From this figure, it can also be observed that the intensity radiation shows an enhancement close to the fiber tip, and the electric field intensities ($|E|/|E_0|$ max) of a p- and s-polarized are 1.52 and 1.89, respectively. In addition, the tapered region is smaller along the axial direction of the fiber tip, and the fiber’s cross-section decreases due to the tapering of the fiber, resulting in the diffractive effect being significantly enhanced and the light escapes to the surrounding area via the evanescent field. The energy of the evanescent field is inherently related to the refractive index, the higher the refractive index of the surrounding medium of the fiber, indicating that the less confined will be the light in the fiber [25]. Therefore, the uncoated tapered optical fiber is poor confinement of light field in a small cross-section area.

Tapered Optical Fiber with Ag Nanoparticles

A tapered optical fiber of the local electric field enhancement is investigated when Ag NPs are coated at the fiber tip. As above, the shape of the fiber tip was determined using the default value. The radius of the Ag NPs is taken as 50 nm and the gap between them is 5 nm. The NPs are 1 nm away from the fiber tip surface. Figure 3 shows a simulated electric field distribution of a tapered optical fiber with different wavelengths of 532, 633, and 785 nm. These results demonstrate that the electric field can be significantly enhanced in p-polarized light due to the light leaking out from the fiber tip surface and excitation of localized surface plasmons (LSPs) between the Ag NPs. Furthermore, the “hot spot” that depends on the interaction between the NPs and the excitation light occurs between the Ag NPs, and its position varies with wavelength. The $|E|/|E_0|$ max arrived at 15.8 in the case of the tapered optical fiber at 532 nm. For s-polarized light, Fig. 4 shows the evanescent field uncoupling the LSPs between neighboring Ag NPs. Obviously, they do provide a reflective layer, like a mirror, that reflects light back into the tip, creating a standing wave [25]. The maximum electric field intensity is 4.46, and the electric field characteristics do not exhibit obvious variers in all wavelengths. Thus, we will focus on p-polarized light in the subsequent analyses.

Furthermore, the optical characteristic of the proposed probes was performed, and transmission spectrums were measured by frequency-domain field and power, and the monitor presented at 20 nm underneath the fiber tip. In Fig. 5a, a peak concave is observed at 490 nm, attributed to the absorption occurring between the Ag NPs, resulting in the transmission spectrum being concaved. For SERS fiber probes, it is necessary to select the appropriate lasers to excite plasmon, which is advantageous in Raman applications and enhanced signals. Thus, we analyze the electric field along a line connecting the Ag NPs at different wavelengths, as shown in Fig. 5b. The results suggest that the electric field intensity near 490 nm is significantly higher than over the whole wavelength from 450 to 800 nm. This
is expected since the fiber tip coated Ag NPs, the dip of the transmission spectrum is the signature of the excitation of the fundamental gap plasmon resonance [25, 29]. On the other hand, the p-polarized light with the electric field perpendicular to the tapered surface of the Ag NPs is coupled to the surface plasmons polaritons (SPPs) supported TM mode in the probes [30].

Parameter Optimization of Tapered Optical Fiber

Notably, the SERS study indicates that optimization geometric parameters of the fiber probes are important since the optimal fiber probes can obtain the most efficient SERS signal and electric field enhancement. Therefore, we have performed simulations for four different parameters, including tip radius, conical angle, Ag NPs size, and the gap between them, to record the effect of electric field using the excitation wavelengths of 532, 633, and 785 nm. A single-valued variable method is used for optimization, other parameters set as default tapered angle ($\theta = 41.2^\circ$), tip radius (50 nm), Ag NPs radius (50 nm), the gap between Ag NPs (5 nm), and the gap between Ag NPs and fiber tip surface is 1 nm. As shown in Fig. 6a, the effect of the tip radius (50 to approximately 500 nm) on the $|E|/|E_0|$ enhancement between the Ag NPs was calculated. Note that the electric field under the wavelength of 532 nm is larger than that of 633 and 785 nm, especially since the tip radius is less than 200 nm. As the tip radius reduces, a more evanescent field outside the walls of the taper is coupled to the NPs, leading to an enhanced electric field between the Ag NPs. In general, the effect of the electric field and emission energy at 532 nm is stronger than a longer wavelength. The effect of the cone angle from 10 to 70° is calculated, as described in Fig. 6b. The electric field fluctuations at excitation wavelengths of 532 and 633 nm are more obvious than those at 785 nm, and the optimum field enhancement is obtained at a cone angle of 25 to 35°, while the electric field variations at the excitation wavelength of 785 nm are not significantly at all conical angles. The effect of the gap between the Ag NPs on the electric field enhancement was investigated, as evidenced in Fig. 6c. The figure indeed shows that the electric field intensity is rapid reduction as the spacing between the Ag NPs increased. In other words, the strongest hotspots exist when the dimers of Ag NPs gap distance are less than 5 nm region [31]. Finally, the effect of the Ag NPs radius was evaluated in size range from 30 to 100 nm, as shown in Fig. 6d. As expected, the electric fields acquired show that the optimal electric field at each wavelength corresponds to different NP sizes. For 532, 633, and 785 nm excitation, the maximum of $|E|/|E_0|$ was obtained when the NPs size of the radius is 55, 70, and 95 nm, respectively. It can be explained that the wavelengths of LSPs are slightly different for certain dimensions of the Ag NPs.

The Tapered Optical Fiber Probe with Substrate

In the above analysis, we discussed the field enhancement characteristics of the proposed probes only included fiber tip-coated Ag NPs. To further improve the electrical field enhancement, we designed a noble metal (Au) substrate located $L = 23$ nm below the probes-tip, as shown in Fig. 7a. The higher enhanced electric fields can be found
between the tip-substrate coupling and between the Ag NPs, as illustrated in Fig. 7b. The coupling field enhancement mainly relies on the excitation wavelength, substrate, and relative distance between the fiber tip and substrate. Here, we mainly pay attention to the excitation wavelength of 785 nm. As shown in Fig. 7c, the field strength of the

![Image](image-url)

**Fig. 7** a Sketch of the structure of tip-substrate coupling with the distance L of 23 nm, b simulated electric field distributions in the x-y plane under the excitation wavelength of 785 nm, c the electric field variation between Ag NPs in different wavelengths with substrate and without substrate, d The distribution of electric field at the tip-substrate and between NPs as the distance L increases, e the distribution of electric field and the effective mode area without substrate and f with Au substrate.
Table 1 The electric field and enhancement factors of the presented probes in different noble metal substrates and excitation wavelengths

| Substrate | $\lambda$ (nm) | $E_{\text{max}}$ (v/m) | EF  |
|-----------|----------------|------------------------|-----|
| Au        | 532            | 23.1                   | $2.9 \times 10^3$ |
|           | 633            | 23.7                   | $3.2 \times 10^3$ |
|           | 785            | 22.3                   | $2.5 \times 10^3$ |
| Ag        | 532            | 33.2                   | $1.2 \times 10^6$ |
|           | 633            | 20.0                   | $1.6 \times 10^3$ |
|           | 785            | 22.4                   | $2.5 \times 10^3$ |

Tip-substrate coupling between Ag NPs is significantly larger than that of the fiber tip without a substrate in the wavelength range of 450–800 nm. At the same time, both curves have similar electric field intensity variations near 490 nm. This again proves that the peak of 490 nm represents the plasmon resonance peak generated between Ag NPs on the fiber tip surface because the position of the peak is not related to the substrate. Figure 7d shows the variation of the electric field in the x–y plane with the gap between the fiber tip-substrate. The gap distance is varied from 23 to 400 nm. It is shown that the strong electric field is reduced as the increase of distance $L$. When the $L$ is less than 26 nm, the maximum of the $|\nabla \times E_{\text{tip}}|_{\text{max}}$ arrived at 22.3 attributed by tip-substrate coupling. Whereas, when the $L$ is greater than 26 nm, the electric field between adjacent Ag NPs is higher than tip-substrate coupling mainly dominated by both plasmonic gap modes and image-force effect [32]. On the other hand, as the distance increases, the field strength between Ag NPs is enhanced, which can avoid the detection distance problem in the application of probe detection. In addition, we investigated the effective mode area in both models that is the tip without substrate coupling Fig. 7e and the tip-substrate coupling Fig. 7f. The latter has a higher enhancement of the electric field and the effective mode area is severely reduced due to strong mode coupling.

Finally, we compared the fields enhancement that two substrate-Au and Ag, were used to evaluate the tip-substrate coupling efficiency. Table 1 shows that field enhancement performance is best for the Ag substrate, followed by Au. In addition, the EF calculations showed that the probes with Ag substrate have stronger EF values at the wavelength of 532 nm. In fact, Au substrates have a more stable EF in different wavelengths. In the actual SERS system, the Ag substrate obviously has a larger SERS signal enhancement than Au substrate. The result of our simulation is consistent with other model simulation obtained in previous reports [33–35], indicating that the model is feasible. In general, above obtained results indicate that the simulation model and calculation results provide a reference for tapered SERS fiber probes applications in the Raman fields.

**Conclusion**

In this study, we have reported a design of a tapered optical fiber probe using Ag NPs deposited on the fiber tip. The electrical field enhancement and spectrum properties of the fiber probe are obtained using the 2D-FDTD method. The analysis shows that the maximum electric field enhancement is related to the transmission spectrum. The probe has a stronger electric field intensity compared to the reported modified Au NPs. The influence of the tip radius, conical angle, Ag NPs size, and gaps between them on the electric field enhanced has been quantified under a typical excitation wavelength of 532, 633, and 785 nm. Moreover, the electric field of the proposed probe is further enhanced from 13.9 to 22.3 times when Au substrate was introduced under the tapered fiber tip. This study can provide theoretical support for the development of tapered fiber probes and has a reference value for the preparation of Raman fiber probes for biosensing applications.

**Author Contribution** Xiaolei Yu and Zhimin Zhao performed the conceptualization, methodology, editing, and overall supervision. Ciyong Gu performed the model, writing, and simulation. Delong Meng contributed to the data analysis.

**Funding** This work was partially supported by the National Natural Science Foundation of China (grant nos. 61771240 and 61475071) and the Six Talent Peaks Project in Jiangsu Province of China (XYDXX-058).

**Availability of Data and Material** Data may be obtained from the authors upon reasonable request.

**Declarations**

**Ethics Approval** Approved.

**Consent to Participate** Approved.

**Consent for Publication** Approved.

**Conflict of Interest** The authors declare no competing interests.

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