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Maximizing Light Coupling Efficiency via LSPR Effect using AuNP-Coated Angle-Cleaved Fiber Probe for Optical Microscopy Application

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ABSTRACT

The development of optical microscopy technology such as near field microscopes crucially relies on excellent efficiency of light coupling. This study investigates the effect of fiber optic probe's cleaved angle on light coupling efficiency by incorporating propagating surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR) phenomena using platinum thin film and gold nanoparticles respectively. The fabrication process started by fabricating the angle-cleaved fiber probes with various angles ranging from 40.08° to 71.00° using heat-and-pull and cleaving techniques. To determine their coupling efficiency performance, a multimode fiber was acted as a transmitter, meanwhile the angle-cleaved probes were functioned as a receiver of specifically a light coupler. Two types of noble metal, namely gold nanoparticles (AuNP) and platinum thin film (Pt) were coated onto the probe to generate SPR for the coupling efficiency enhancement. The effects of significant factors such as cleaved-angle, operation wavelengths and types of metal; to the coupling efficiency were studied. It was found that the application of gold nanoparticles resulted in a noticeable increase in light coupling efficiency that exceeding 90%, demonstrating their effectiveness in LSPR enhancement. We noticed that the deployment of a greater cleaved angle at 71.00° resulted in the greatest coupling efficiency due to the reduction of back-reflection loss indicating the crucial fiber structure in light coupling. Introducing gold nanoparticles as LSPR material resulted in a more stable and enhanced coupling efficiency response compared to platinum. In conclusion, the enhanced localized surface plasmon resonance (LSPR) effect produced a significant evanescent field that was able to improve optical confinement. These findings highlight a cost-effective and scalable approach for developing high sensitivity probe with strong potential applications, especially in optical microscopy fields.

1. Introduction

Optical microscopy has become one of the foundational tools used in scientific research, enabling the visualization of micro and nanoscale structures that provide high spatial resolution [1]. Conventional microscopy enables efficient imaging, however advanced applications such as near-

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field optical microscopy continue to evolve for its ability to overcome diffraction limit. Nonetheless, the performance of this technology depends on the efficiency of light coupling between the optical source and the fiber probe. Insufficient light coupling leads to reduce in image resolution and low measurement sensitivity [2]. Therefore, optimizing fiber probe structure to maximize light coupling is essential for high-performance microscopy applications [3,4].

One effective approach in improving light coupling involved modifying the geometry of the fiber. Standard flat-cleaved optical fibers often suffer from mode mismatch and limited field confinement particularly at the fiber sample interface [5]. These limitations reduce the amount of usable optical power delivered to the imaging region. To address these limitations, modifications such as angle-cleaved fiber ends have been proposed. Conventional methods such as flame brushing, heat-and-pull and chemical etching produced angle-cleaved fiber probe with inconsistent structure, fiber probe surface irregularities, and unstable optical properties which limit their effectiveness in delivering efficient light coupling for high-resolution microscopy [6-8]. Angle-cleaved fiber probe offers several advantages, including reduced back-reflection, help in enhancing the ability to direct the optical field toward the target region and improving the coupling performance [9]. In angle-cleaved fibers, the end face is inclined by an angle θ, redirecting the reflected beam away from the fiber axis. This significantly reduces the spatial and angular overlap between the reflected field and the guided mode, thereby suppressing backward coupling while preserving forward transmission. Consequently, optical return loss values better than −40 dB are commonly achieved, improving coupling stability and reducing laser feedback without additional optical components [10]. The cleaved angle plays a crucial role in determining the light propagation direction and confinement, making it an important parameter in fiber probe design.

Despite the modification of the fiber structure, the incorporation of localized surface plasmon resonance (LSPR) help in light enhancement. LSPR is an optical phenomenon that occurs when the incident light interacts with conductive nanoparticles that have smaller wavelengths than the incoming light inducing a collective and coherent oscillation of surface conduction electrons in resonance with the electromagnetic field [11,12]. Unlike surface plasmon resonance (SPR), which propagates along continuous metal surfaces, LSPR are well confined to the individual nanoparticles surface. When the resonance condition is achieved, these metal nanoparticles show a pronounced absorption band resulting in enhanced electromagnetic field [13]. In recent studies, particle optical wave excitation shows in noble metal nanoparticles have also been reported further highlighting the significance of LSPR in nanoscale light matter interactions [14].

Previous approach to enhance the sensitivity and resolution of optical fibers involved coating fibers with two-dimensional materials such as graphene and molybdenum disulfide. Recent research trends focus on noble metal such as gold (Au) often in form of nanoparticles (AuNPs) [15]. Among all the noble metals, gold is commonly distinguished as superior optical responses due to its stability, light scattering properties and large enhancement ability of the local electromagnetic field [16]. The performance of LSPR induced fiber probes depend on deposition process of the noble-metals where technique such as seed-mediated growth technique and drop-casting ensure uniform nanoparticle thickness distribution needed for stable plasmonic excitation on angle-cleaved fibers [17]. Drop casting technique is commonly used to prepare modified electrodes with metal nanoparticles for various applications including optical microscopy applications due to its simplicity and less costly advantages [18-20]. These enhancements arise from the localized surface plasmon resonance (LSPR) phenomenon, where the free electrons on the metal surface collectively oscillate in response to incident light. The resulting resonance led to intense scattering of light which valuable for imaging, sensing and microscopy applications. Integrating noble metal coatings with angle-cleaved fiber probes help in increasing efficiency of light coupling.

The main challenge in fabricating the angle-cleaved fiber probe for optical microscopy is the fabrication process, primarily due to the advanced fabrication techniques required high-end, expensive setup and often lacked in precision for consistent optical performance. Recent study in plasmonic technology demonstrated the potential of localized surface plasmon resonance to enhance the evanescent field strength at the fiber probe structure, thereby improving light interaction in microscopy [21,22]. Therefore, this research proposed the fabrication of various angle-cleaved fiber probes using heat-and-pull and cleaving techniques, combined with noble-metal-induced plasmonic enhancement, to maximize light-coupling efficiency. In this study, the effects of propagating surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR) were compared using platinum thin films and gold nanoparticles, and their influence on the coupling efficiency of angle-cleaved fiber probes was investigated. The findings of this work are benefited to the field of optical microscopy, particularly in applications requiring strong local field enhancements, improved signal strength, and higher imaging sensitivity.

2. Methodology

2.1 Fabrication of Angle-Cleaved Fiber Probe using Heat-and-Pull and Cleaving Techniques

The angle-cleaved fiber probes were fabricated using single mode fiber. The probes were initially invented using a Sumitomo Z2C core-alignment fusion splicer, with parameters such as arc duration, arc power, and pulling distance precisely controlled to ensure consistent tapered formation. Once the bi-tapered structure was successfully obtained, the fiber was cleaved using high-precision fiber cleaver to create the angle cleaved geometry. Five samples were prepared with each of the samples exhibiting a distinct angle which varies from 40.08° to 71.00°. Figure 1 shows the fabrication process of angle-cleaved fiber probes using cleaving technique. A digital microscope (Brand: Dino-Lite) was used to characterize the structural characteristic of the various angles fabricated fiber probe after the cleaving process. The microscope provided magnification in large scale up to 575X, allowing detail visualization of surface uniformity. The cleaved angle was measured directly from the microscope images.

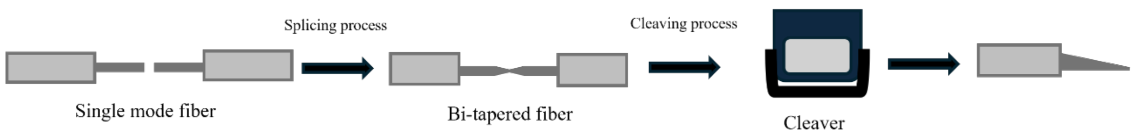


Fig.1. Process to fabricate angle-cleaved fiber probe by using heat-and-pull and cleaving techniques

2.2 Deposition Technique of Platinum-Gold Nanoparticles (Pt-AuNPs) on Angle-Cleaved Fiber Probe

To generate surface plasmon resonance phenomena, two types of samples were prepared which are Pt-coated angle-cleaved probe and AuNP angle-cleaved probe. The deposition of Pt thin film was performed to coat the angle-cleaved fiber probe for the purpose of analyzing their sensitivity and to enable propagating SPR functionalization. The deposition process was carried out by using a sputter coater (Brand: JEC-3000FC Auto Fine Sputter Coater). The probes were mounted onto a fiber holder to ensure firm positioning throughout the sputtering process, while a glass slide was included in the chamber to support the probe arrangement. During the deposition process, Pt was sputtered onto the probe surface under controlled sputtering parameters, which operated at a deposition time of 15 seconds with a current setting of 10 mA, ensuring the formation of a uniform layer of platinum thin film that acts as a precursor for subsequent nanoparticle deposition and contributes to improve the overall optical sensitivity of the fabricated probes.

Next, gold nanoparticles (AuNPs) with an average diameter of 50 nm (Brand: Sigma-Aldrich) were deposited onto the bare angle-cleaved fiber probe, functioning to introduce LSPR effect as shown in Figure 2. The deposition process was conducted using a drop-casting technique. The process began with attaching the fiber probes onto the glass slide and placed them inside a petri dish to ensure the stability. Then, a small volume of the AuNP solution about 5μl was drop-casted on the cleaved part, and the petri dish was sealed with parafilm to minimize the contamination from external sources such as dust. The samples were dried in a furnace at a fixed temperature of 80 °C for approximately 30 minutes to ensure firm attachment of the nanoparticles. The optical properties of Pt and AuNPs were characterized by using UV-ViS spectroscopy.

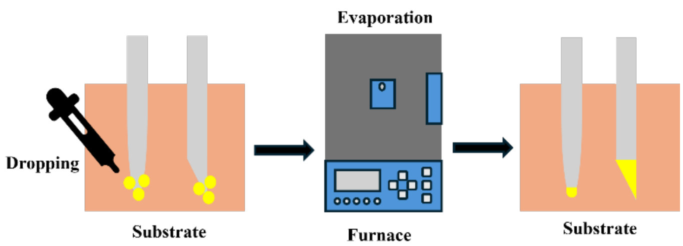


Fig. 2. Drop casting procedure of gold nanoparticles on angle-cleaved fiber probe

2.3 Investigation of Power Coupling Efficiency of Metal-Coated Angle-Cleaved Fiber Probes

Figure 3 shows the schematic diagram of light coupling setup by using metal-coated angle-cleaved fiber probe. An optical light source (OLS) (Brand: AFL-Noyes CSS-SM) transmitted light through the multimode fiber. An optical power meter (OPM) (Brand: AFL-Noyes CSS-SM) which was connected to the Au and Pt-coated angle-cleaved fiber played an important role to couple the transmitted light. Two types of operating wavelength were deployed which are $\lambda_1 = 1310\ nm$ and $\lambda_2 = 1550\ nm$. The presence of plasmonic field due to the interaction between light and metal able to enhance the coupling efficiency. The power coupling efficiency of angle-cleaved fiber probe, η was calculated by determine the power ratio from the input power (P_1), to the measured output powers (P_2), expressed as:

$$\text{Coupling efficiency, } \eta = \frac{P_2}{P_1} \tag{1}$$

where P_1 and P_2 are the measured optical power values gained from the optical power meter converted from nanowatts (nW) to watts (W). The ratio of optical power P_2 to P_1 provide coupling efficiency reflects the effectiveness of power transfer between the probes. By varying the coupling distance from 1 mm to 5 mm, the coupling efficiency of angle-cleaved fiber probe, η was determined.

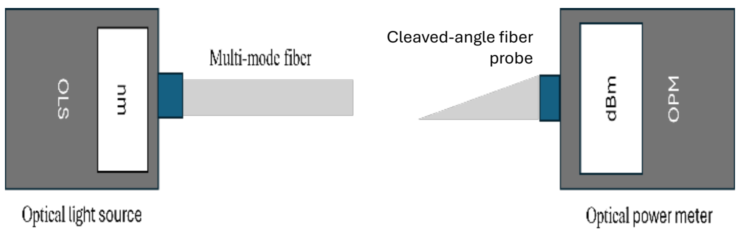


Fig. 3. Schematic diagram of light coupling using angle-cleaved fiber as coupler

3. Results

3.1 Characterization of Platinum Thin Film and Gold Nanoparticles via UV-ViS

Figure 4 illustrates the UV-ViS absorption spectrum of platinum thin film showing notable peaks and variations in absorption at specific wavelengths. The absorption increased between 200-400 nm, maximizing around 300-350 nm with the absorption value ranges around 0.28 a.u to 0.30 a.u. Figure 5 exhibits the analysis of absorption spectrum of gold nanoparticles using UV-Vis. The UV-Vis absorption spectrum of the gold nanoparticles solution graph exhibited a prominent peak around 520-530 nm, confirming the characteristic of the surface plasmon resonance (SPR) of gold nanoparticles with an absorbance intensity rate approximately 0.5 a.u, indicating an acceptable concentration of nanoparticles within the solution. As the wavelength increased beyond the resonance region, the absorbance gradually decreased, which was consistent with the expected optical behavior of gold nanoparticles. This spectral verified the successful synthesis of gold nanoparticles making them suitable for plasmonic enhancement in optical microscopy applications.

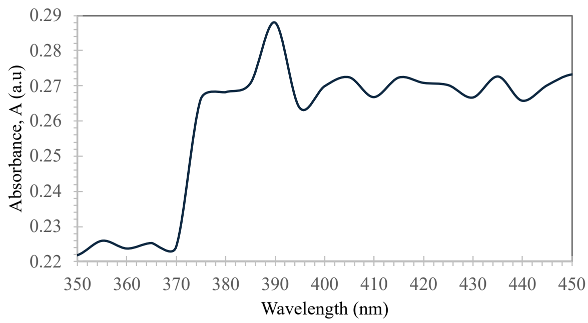


Fig. 4: UV-ViS absorption spectrum of platinum thin film

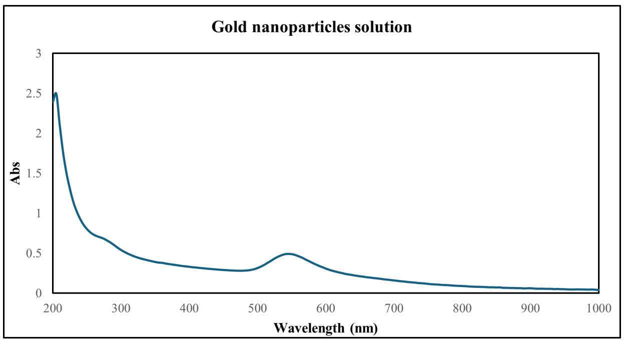


Fig.5. Absorption spectrum of gold nanoparticles solution

Figure 6 displays the image of a gold nanoparticles solution coated on the fiber, captured using the Field Emission Scanning Electron Microscopy (FESEM). It showed that gold nanoparticles managed to successfully adhere to the surface of the fiber through the deposition process. The high resolution FESEM image captured at a magnification of 25K clearly revealed the nanoparticles' morphology and distribution. This uniform gold nanoparticles arrangement was crucial for ensuring efficient plasmonic interaction and reliable optical enhancement during optical coupling measurements.

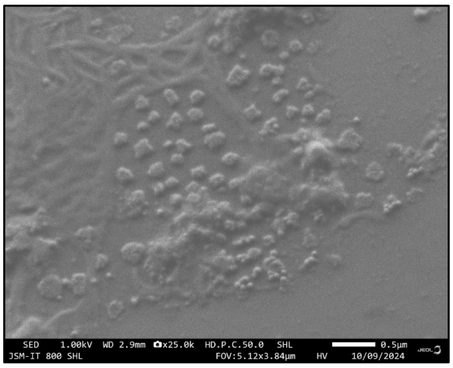


Fig. 6. FESEM image of gold nanoparticles coated on angle-cleaved fiber probe

3.2 Structural Analysis of Angle-Cleaved Fiber Probes using Digital Microscope

Table 1 shows the cleaved-angle measurement for all five fiber probes samples. Figure 7 displays the corresponding digital microscope image of the fabricated probes. The angle-cleaved fiber probes were examined using digital microscopes to evaluate their structural condition following the cleaving process, including the presence of defects and the accuracy of the cleaved angle. Obviously, by manually controlling the angle, the desired cleaved angle was successfully fabricated as depicted in Figure 8. Figure 9 shows the platinum coated angle-cleaved fiber probe image under digital microscope. The presence of greyish or blackish colour on the probe surface indicating successful adhesion of platinum coating.

Table 1
Angle measurements of angle-cleaved fiber probes

Probe	1	2	3	4	5
Angle (degree)	40.08°	58.78°	59.32°	69.62°	71.00°

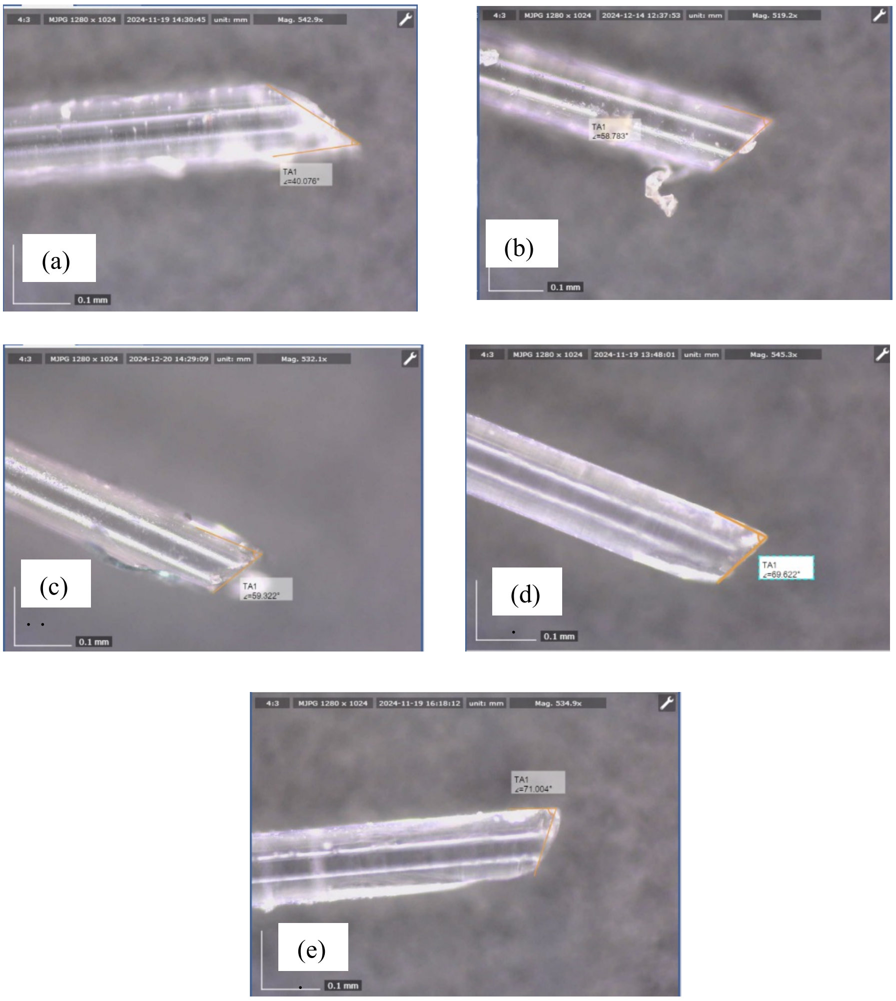


Fig. 7. Image of angle-cleaved fiber probes captured under a digital microscope with various angle (a) 40.08° (b) 58.78° (c) 59.32° (d) 69.62° (e) 71.00°

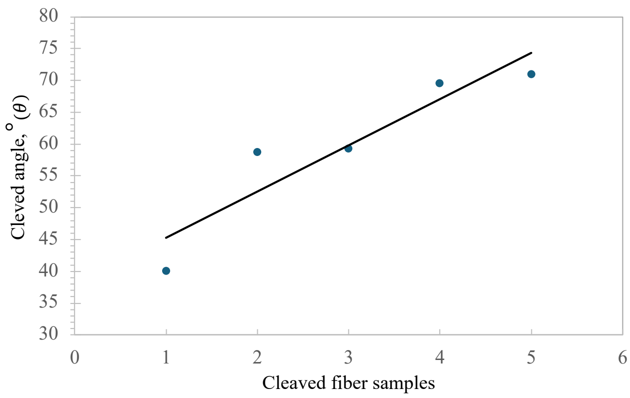


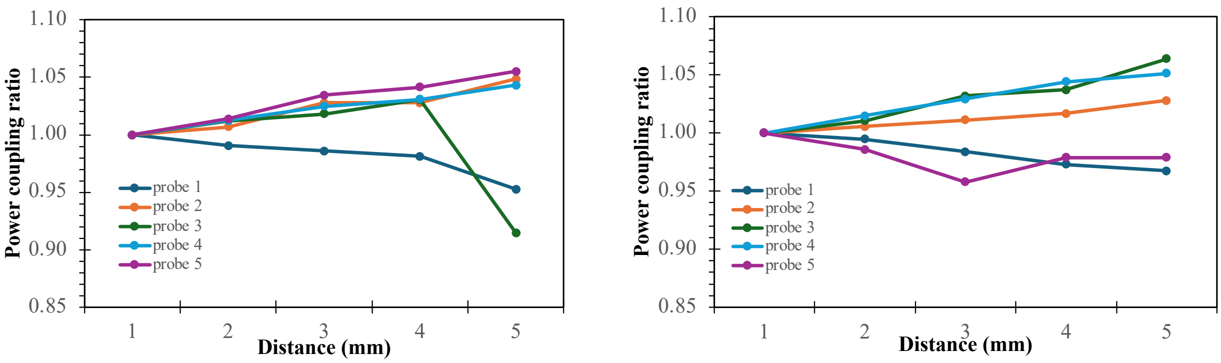
Fig. 8. Five samples of cleaved-fiber optics with various angle using heat-and-pull and cleaving techniques

Fig. 9. Image of platinum coated angle-cleaved fiber probe under digital microscope

3.4 Effect of Power Ratio, p/p on the Coupling Distance, d (mm) for Various Angles Fiber Probes
3.4.1 AuNP-coated angle-cleaved fiber probe

Figure 10 (a) shows the power coupling ratio graph for five samples of AuNP-coated angle-cleaved fiber probes at varying distances between 1 mm and 5 mm using 1310 nm operating wavelength. Probe 1 showed a drop in power ratio value down to 0.91 a.u as the coupling distance increased. Probe 2 initially increased slightly to 1.00 a.u at 2 mm and maintained the values up to 1.04 a.u at 5 mm, indicating stable coupling performance. Probe 3 exhibited an increase to 1.01 W at 2 mm, maximizing at 1.03 a.u at 4 mm, before declining to 0.95 a.u at 5 mm, suggesting variability in performance. Probe 4 consistently increased, peaking at 1.04 a.u at 5 mm, showing strong coupling efficiency. Probe 5 demonstrated the highest stability, maintaining values around 1, maximizing at 1.06 a.u at 5 mm, illustrated the most consistent performance across distances.

Figure 10 (b) portrays the coupling ratio of AuNP-coated angle-cleaved fiber probe at 1550 nm. Probe 1 shows a consistent decrease in power ratio with increasing distance, starting at 1.00 a.u and ending at 0.97 a.u at 5 mm. Probe 2 had a slight decrease at the start, with values around 0.99 a.u at 2 mm, and stabilized at 0.98 a.u at 5 mm. Probe 3 increased steadily, exhibits a higher peak at 1.03 a.u at 5 mm, indicating strong coupling performance. Probe 4 displayed a continuous increase, reaching 1.05 a.u at 5 mm, showing excellent coupling efficiency. Probe 5 followed a similar trend to Probe 3, peaking at 1.06 a.u at 5 mm, reflecting the highest stability and performance at longer distances. It should be noted that few output shows the light coupling ratio greater than 1. This phenomenon occurs due to light collection enhancement and mode confinement enabled by localized surface plasmon resonance at the metal-coated fiber probe [23].



(a) (b)

Fig. 10. Power ratio graph of AuNP-coated angle-cleaved fiber probe (a) 1310 nm (b) 1550 nm

3.4.2 Pt-coated angle-cleaved fiber probe

Figure 11 (a) shows the graph of Pt-coated angle-cleaved fiber probe at 1310 nm. It exhibited similar coupling characteristics as AuNP-coated angle-cleaved fiber, starting with a power ratio of approximately 1.10 a.u at 1 mm. As the distance increased, the power ratio gradually decreased, reaching a value of about 0.75 a.u at 5 mm. The trend indicated a slightly lower coupling efficiency compared to the gold coated angle-cleaved probe at this wavelength, particularly at longer distances. However, the angle-cleaved fiber probe showed consistent behaviour across the five tested probes, demonstrating good reproducibility of the fabrication process. This probe was a viable alternative for coupling applications at 1310 nm, particularly when the probe geometry of the angle-cleaved fiber probe is preferred.

The light coupling ratio of Pt-coated angle-cleaved fiber probe at 1550 nm is illustrated in Figure 11 (b). At a wavelength of 1550 nm, the fiber probe exhibited coupling characteristics that were comparable to those of the Au-coated angle-cleaved fiber. The power ratio started at approximately 1.05 a.u at 1 mm and decreased steadily to around 0.75 a.u at 5 mm. The consistency of the power ratio trend across all five probes demonstrated the reliability of the angle-cleaved fiber probe design.

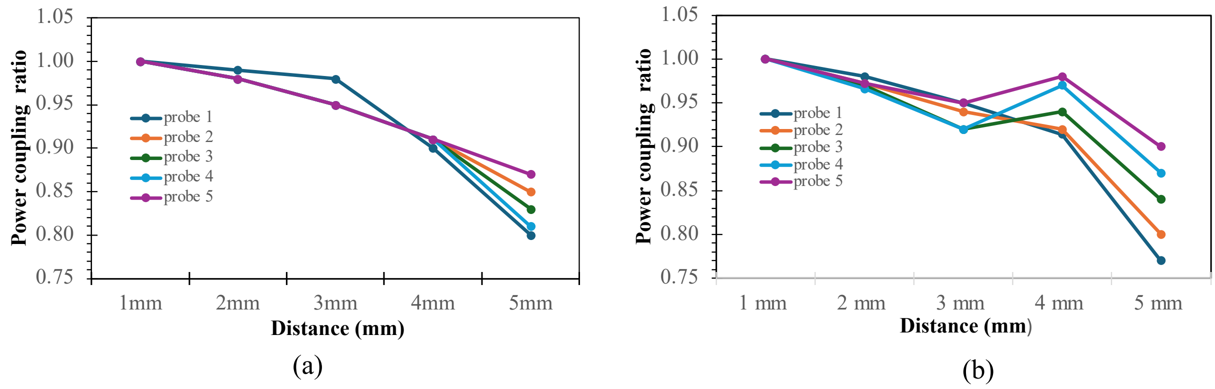
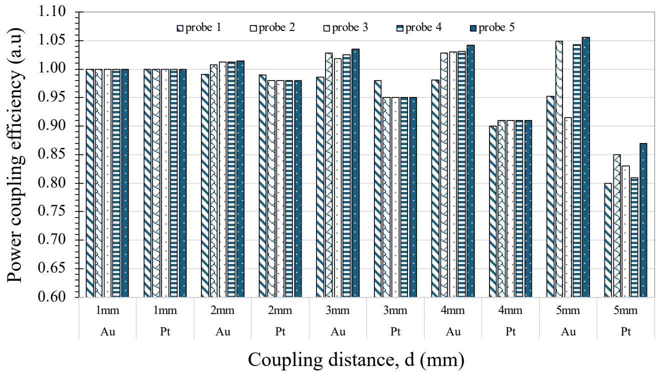


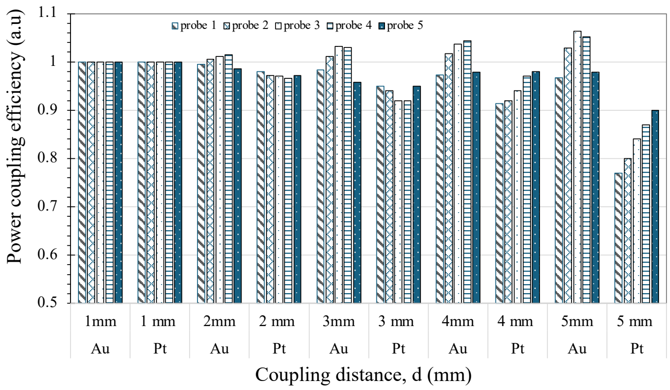
Fig. 11. Power coupling ratio graph of platinum (Pt) coated angle-cleaved fiber probe (a) 1310 nm (b) 1550 nm

3.4.3 Analysis of power coupling efficiency between AuNP and Pt-coated cleaved angle at 1310 nm and 1550 nm operating wavelength

Comparison analysis between both types of metal coated probe shows a significance difference as the coupling distance were set at 3 mm and above as illustrated in Figure 12. Note that, under this configuration, the air turbulence mainly affected the light propagation in free space considering an air turbulence factor [22]. At d=3mm, the coupling efficiency of AuNP-coated probe showed an excellent coupling efficiency, η in which 100% of light was successfully coupled to the probe using probe 5 (θ=71.00°) compared to Pt-coated probe (η=98%) as λ=1310 nm. Similar pattern was observed as the wavelength increased to λ=1550 nm where the coupling efficiency increased to 5 % as the Pt was replaced with AuNP. However, the coupling efficiency of the AuNP-coated probe exhibited lower stability than that of the Pt-coated probe at the same coupling distance, mainly due to differences in the material and coating structure. The platinum layer was more uniform than the gold coating because Pt formed a continuous thin film, whereas AuNP consisted of discrete nanoparticles. The interaction between light and the metal induced surface plasmon resonance, producing a stronger evanescent field with varying intensities as light interacted with materials of different structures. When the coupling distance was increased to *d* = 4 mm, a similar trend was observed, where the power coupling efficiency increased by approximately 9 %, from 91 % to 100 %, as the cleaved-angle probe (Probe 5, θ = 71.00°) was replaced with the AuNP-coated probe at λ = 1310 nm. At 1550 nm, the overall analysis indicated improved coupling efficiency when using the AuNP-coated probe. At the maximum coupling distance of *d* = 5 mm, both wavelengths exhibited excellent coupling efficiency as the Au-coated probe with a cleaved angle of θ = 71.00° was employed.



(a) 1310 nm



(b) 1550 nm

Fig. 12. Coupling efficiency comparison between AuNP and Pt-coated cleaved-angle probe as light coupling distance vary (a) λ=1310 nm (b) λ=1550 nm

As the coupling distance increased from 3 mm to 5 mm, the advantage of the AuNP-coated angle-cleaved fiber became increasingly evident, as it was able to maintain a coupling efficiency exceeding 90%. In contrast, the performance of the Pt-coated probe exhibited a declining trend, with the coupling efficiency dropping to 76%. Furthermore, the application of gold nanoparticles resulted in a noticeable increase in optical power coupling ratio, demonstrating their effectiveness in LSPR enhancement. This condition allows enhanced light–matter interaction and improved absorption at sub-wavelength scales, which is linked to easier coupling of light [24].

4. Conclusions

This study presents an alternative light-coupling approach based on localized surface plasmon resonance (SPR), utilizing an AuNP-coated angle-cleaved fiber probe operated at a 1550 nm laser wavelength, demonstrating strong potential for advanced optical microscopy applications. AuNP-coated angle-cleaved fiber probes with maximum angle of 71.00° demonstrated superior coupling efficiency compared to Pt-coated probes. The unique nanostructural properties of AuNPs significantly enhanced the evanescent field, providing stronger signal amplification than Pt thin films.

The use of a single layer of gold nanoparticles led to a significant increase in light-coupling efficiency, exceeding 90% compared to platinum thin films, highlighting their effectiveness in enhancing localized plasmonic interactions. Nevertheless, a significant drawback of AuNPs was their reduced stability, arising from the challenge of controlling uniform interparticle spacing. Although the angle-fiber was capable of enhancing light coupling efficiency, its manual fabrication process presented several drawbacks, including low repeatability and limited controllability. To overcome these issues, alternative deposition techniques such as seed-mediated growth and auto-cleaving methods are proposed for future work, as they are expected to enable precise control over interparticle spacing and cleaved-angle geometry.

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