Covering a fiber taper with a refractive index matching gel residue: a significant increase in evanescent-wave signal collection efficiency

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A novel optical fiber evanescent-wave (EW) sensing platform combining a taper and a refractive index (RI) gel residue is proposed. The platform includes two identical large core multimode fibers perpendicularly positioned to each other: one for excitation light delivery (i-fiber) and one for EW fluorescent signal collection (r-fiber). One end of the r-fiber is decladded to expose a segment of a cylindrical fiber core terminated with a taper. A small drop of rhodamine 6G (R6G) solution sample is distributed in such a way that it surrounds the side wall of the cylindrical portion of the core and covers the i-fiber end face. The fluorescent signal is recorded under the following conditions: 1) the entire taper is exposed to air; 2) the entire taper is immersed into a large gel block; 3) the taper is covered with a gel residue. A dramatic rise of the fluorescence signal is observed in the third case, which is over 20 times more than the level achieved from the first two cases. We reveal that the intensive mode coupling in the sandwiched air-gel-taper architecture accounts for this phenomenon, which is discussed in detail.

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The optical fiber evanescent-wave (EW) sensing platform has extremely high signal-to-noise ratio (SNR) when dealing with a surface event. Thus, it has become one of the preferred tools for chemical and biological sample analysis. In addition, because it uses a side wall of a hair-thin and flexible optical fiber core as a sensing surface, this platform is particularly useful when done *in situ*; it can respond rapidly, is portable, cost-effective, and is easy of remote monitoring[1].

However, this unique built-in advantage comes at a cost: the optical signal collected from the surface is much weaker compared with many counterparts that are not based on EW[2]. Moreover, the optical fiber EW platform usually includes a much smaller sensing surface and various compact optical and electronic components, whose performances do not match those achievable in high-end analytical instruments.

So far, tremendous efforts have been exerted to enhance the signal collection efficiency of various optical fiber EW sensing platforms[3]. However, long sensing length from at least several centimeters, very low efficiency in the use of excitation power, and strong stray excitation light appearing at the detector are still common drawbacks. In this letter, we present a practical solution to address these concerns by combining a taper and a refractive index (RI) gel residue to our previously established optical fiber EW sensing platform[4].

The proposed platform was established with two identical BFL37-400 multimode fibers with core / cladding / jacket diameter of 400/430/730 μm and numerical aperture (NA) of 0.37 (Fig. 1). They were perpendicularly positioned to each other: one for excitation or illuminating light delivery called i-fiber, and another for EW from fluorescent signal receiving called r-fiber. One end of the r-fiber was decladded to expose a segment of fiber core to air. A taper was created by simply pulling the fiber end when heating the middle of the exposed segment with a flame. As a representative of regular fluorescent samples, the water-diluted rhodamine 6G (R6G) liquid sample droplet was used to cover the i-fiber end face and surround the r-fiber core side wall. Surface tension served to hold the droplet in position as long as the distance of the two fibers was sufficiently close. A laser diode (LD) operating at 532 nm with approximately 3-mW output power was coupled into the i-fiber. A USB 2000 palm-held spectrometer (Ocean Optics^{TM}) connected with a computer was used to monitor and record the signal. The maximum fluorescent signal level was identified by simply adjusting the i-fiber to create an offset as described in the previous report[4,5]. RI matching gel (RI = 1.463) block was used to investigate its effect on the collection of the fluorescent signal.

In the experiment, the spectrum of the fluorescent signal was recorded under the following conditions: 1) the entire taper was exposed to air; 2) entire taper was immersed into a large gel block; 3) the taper was covered with a gel residue.

Figure 2 illustrates the results for three cases. There was no significant difference in the fluorescence signal intensity at the peak of fluorescence spectrum (around 550 nm) between cases ① and ②. This indicates that the recorded signal from the taper immersed in air or in bulk gel is solely provided by the right traveling fluorescent light $I_0(+)$ (Fig. 1). The left traveling signal $I_0(-)$

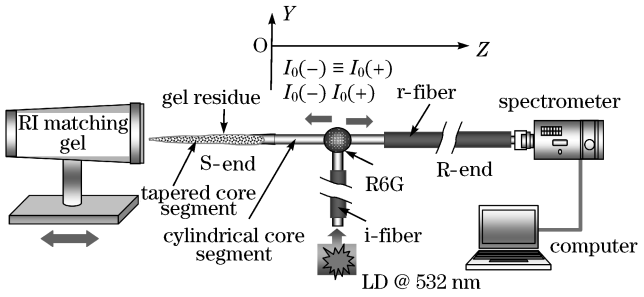

Fig. 1. Optical fiber EW sensing platform for the investigation of the effect of the RI matching gel and the taper on the EW based on fluorescent signal collection.

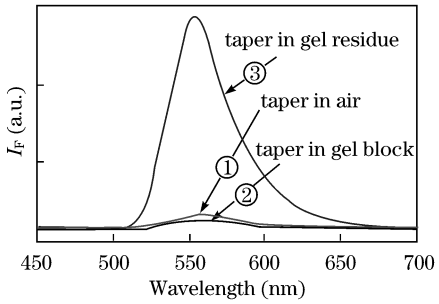

Fig. 2. Experimental results illustrating a significant increase of fluorescent signal collection efficiency when the RI matching gel residue is present on the taper.

simply leaked out of the taper. Although the air or gel block caused the taper to change behavior from a well-confined waveguide (air cladded) to a completely leaky waveguide (gel block cladded), it can provide an infinite isotropic medium to direct all rays carrying the left travelling power $I_0(-)$ out of the taper in fixed directions and then vanish. In opposition to this observation and mechanism, however, spectrum ③ indicates a remarkable rise of more than 20 times the EW fluorescent signal at 550 nm. This was observed when pulling out the gel block, leaving only a trace amount of gel residue covering the taper surface.

This surprising phenomenon is interpreted as follows: in the cylindrical segment of the fiber with droplet, the excited fluorescence is coupled into the fibre core by way of EW, and travels to both sides along the fiber. The EW power to the left and the right sides are represented by $I_0(-)$ and $I_0(+)$, respectively. The initial fluorescence power from the R6G satisfies the condition of $I_0(-) \equiv I_0(+)$ due to the symmetrical architecture formed by the laser, the r-fibre, and the R6G droplet. These EW rays are carried mainly by the modes close to the cut-off, including a part of the guided modes near the cut-off, and a large amount of tunnelling modes just below it[5]. When $I_0(-)$ arrives at the taper, these modes are converted to even higher order modes since the taper is a low-to-high-order mode converter to the incoming light. These modes belong to the category of leaky modes for whatever medium surrounding the taper. These modes cause the fluorescence power $I_0(-)$ to vanish if the cladding is isotropic and infinite. For $I_0(+)$ EW light, when it travels along the fiber core without cladding into the region covered with cladding, a mode conversion occurs. Many light modes (higher order modes) become inhibited, causing high loss of EW power. Therefore, in cases ① and ②, almost all the $I_0(-)$ power leaks out from the S-end, and the $I_0(+)$ power is inhibited by cladding. This mechanism leads to low detectable signals in cases ① and ②.

The gel residue, on the other hand, manifests a substantially different behavior. The gel residue serves as a cladding with limited thickness and with irregular shape across the covered surface. As a result, all the leaky rays carrying $I_0(-)$ can experience a large amount of random back and forth reflections and/or refractions between the taper and the gel residue surfaces. We can also consider the gel residue cover as a second waveguide with an arbitrary profile, which is a trap for these rays. This random process resembles the fluorescent light coupling process occurring in the R6G droplet-covered core side wall surface. The process transfers part of the power $I_0(-)$ back to the modes that are able to propagate along the fiber to the detector, leading to the rise of the fluorescent signal at the R-end (Fig. 1). Another surprise arises from the scale of the signal level in case ③, which doubles the level of cases ① or ② and increases them by more than 20 times. We believe this EW power collection increase mainly emanates from two mechanisms. The first mechanism is obviously from the optimized offset between i- and r-fibres, as detailed in our previous work[4]. When the r-fiber is ended with a perfect end face, the detected power at the R-end comes solely from $I_0(+)$, since $I_0(-)$ simply disappears in the free-space after encountering the end face. This mechanism, however, suffers serious V-number mismatch[6]. The V-number mismatch causes enormous EW power loss when the two fiber segments have substantially different V-numbers. This occurred in our previous work and limited the EW power collection increase. The second mechanism is from the gel covered taper. The taper reduces the V-number mismatch problem efficiently through its gradually reduced diameter. To use this feature, however, tuning of the $I_0(-)$ to the backward direction is required, which is not possible with the taper alone; the introduction of the gel residue serves such purpose. When the taper is covered with gel residue, the limited thickness of the gel and its defects—characterized by surface roughness, gel distribution, and deviation of the taper profile from the symmetrical axis—can force the occurrence of an intensive mode coupling associated with $I_0(-)$ and trigger the backward tuning process. The percentage of $I_0(-)$ that eventually arrives at the R-end is highly affected by these defects. However, it is the taper that converts all modes close to cut-off that are associated with the power $I_0(-)$[6] to leaky modes, exposing their mode fields almost completely to the gel layer. Only under such situation can a more efficient mode coupling within the gel be enabled. Again, due to reduced V-number mismatch of the taper, a much larger fraction of the returned $I_0(-)$ can be detected at the R-end compared with its cylindrical fiber counterpart. Hence, we conclude that the observed EW power increase of over 20 times is the result of the highly efficient mode coupling triggered by the combined effects of the taper and the thin gel layer, which is not experienced by the right traveling fluorescent power $I_0(+)$.

The low signal levels of curves ① and ② reflect the limited capability of most of the EW-based platforms in collecting EW signal. In a traditional optical fiber EW platform, it is preferred that one fiber be used for both excitation and signal collection purposes, which is an advantageous option. However, this is accomplished by adding some complex free-space optic elements at one fiber end. In this case, the excitation power is also generated as an EW form, but is substantially weaker and makes the overall signal collection capability even worse. The well-known solutions to this challenge include using a taper to maximize the EW forming the excitation power level in the cladding side, or increasing the interactive length between the fiber and the sample to accumulate the power. Either way, a larger sample length from several centimeters to several meters is required. In contrast, the platform illustrated in Fig. 1 uses a taper covered with gel residue to create an intensive mode coupling process and increase the collectable EW power level.

The defects related to EW power rise might pose the problem of repeatability of measurement since defects distribution is not easy to control. This is confirmed by repeating the experiments, which reveals that the peaks of the fluorescent spectra from these experiments are not at the same level. However, we also found that the contribution of $I_0(-)$ introduced by thin gel layer and the taper still dominated the overall detected EW power level in each experiment because the power $I_0(-)$ was distributed to the large amount of leaky modes associated with rays with numerous different angles. As long as there were defects, one group of rays with proper angles interacted with the defects and became tuned to the rays that arrived at the R-end. The relocation or change of defects can move such an interaction to another proper group of rays and raise the EW power at the R-end at the same time.

In conclusion, we have demonstrated an EW signal increase of over 20 times using a RI gel residue-covered fiber taper in comparison with a simple optical fiber EW sensing platform. The mechanism behind this signal increase is neither from the signal accumulation effect through a long fiber length, nor from the taper-assisted EW from excitation and EW signal light enhancements, which requires the insertion of the taper into the sample. Instead, the sample has been positioned at the cylindrical portion of the fiber core side wall surface. Its volume is in droplet form and is about 2 mm in diameter. The entire platform is elegant and offers an excellent solution to applications requiring in-situ operation, fast response, high sensitivity, portability, cost-effectiveness, and remote monitoring capabilities.

For our current gel residue and taper platform, defect distribution may not be easy to control, and EW power collection capability may vary among sensors although they are built by identical processes. However, repeatable results can still be achieved for each individual sensor as long as these defects do not change their positions in their service life cycle. Permanently fixed defects may be achieved using the sol-gel process generated film to replace the RI gel residue since it prevents shifts of the defect locations that may be caused by the shape change of the very soft RI gel.

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