

Study on Conical Fiber Optic Triethylamine Gas Sensing Technology Using IDT-CN Sensitive Thin Film

Wenxuan Wang

*School of Changwang, Nanjing University of Information Science and Technology, Nanjing, China,
736011848@qq.com*

Abstract. Triethylamine is a typical volatile organic amine gas that requires reliable detection in industrial production, environmental monitoring, and biomedical applications. To meet the detection needs of triethylamine gas, this paper presents a fluorescence sensing method based on IDT-CN sensitive film and the evanescent wave enhancement effect of conical optical fibers. By analyzing the excitation effect of conical optical fibers on the surface fluorescent layer, two organic semiconductor materials were compared. The conical optical fibers were hydroxylated with the guppy solution, and then the IDT-CN was loaded by the pull-off coating method. A full-fiber detection system containing a 532 nm laser, optical fiber circulator, filter, gas chamber, and spectrometer was built. The experiments show that the probe exhibits significant fluorescence quenching under the action of triethylamine, with a quenching rate of 96.2% under saturated vapor; after vapor dilution by 2, 4, 8, 16, and 32 times, the quenching rates are 86.7%, 58.5%, 54.6%, 53.4%, and 37.7% respectively, decreasing with the decrease in concentration. The study demonstrates the feasibility of combining the conical optical fiber evanescent wave with IDT-CN for the detection of triethylamine, providing a reference for miniaturized and high-sensitivity fiber fluorescence gas sensors.

Keywords: Conical optical fiber, IDT-CN, Evanescent wave, Fluorescence quenching, Tert-butylamine gas detection

1. Introduction

In the field of gas detection, traditional methods mainly include gas chromatography-mass spectrometry (GC-MS), electrochemical sensors, and semiconductor sensors, etc. Although GC-MS has high detection accuracy, its equipment is large in size, operation is complex, and the analysis cycle is long, making it difficult to meet the requirements of real-time in-situ detection; electrochemical sensors have a simple structure, but they are easily affected by humidity, temperature and interfering gases, and their long-term stability and selectivity remain inadequate. Overall, the existing technologies generally have shortcomings such as large volume, poor real-time performance, weak interference immunity, and difficulty in remote detection.

Optical fiber gas sensors have received widespread attention due to their advantages such as small size, resistance to electromagnetic interference, and suitability for long-distance transmission. In the optical fiber sensing structure, the conical fiber can effectively enhance the evanescent field

due to its special geometric structure, allowing the optical field to extend more into the external environment, thereby enhancing the interaction between light and the sensitive material. The gas sensing method based on the fluorescence quenching mechanism has the advantages of intuitive response and sensitive detection, and the selection of sensitive materials is the key to determining the sensing performance.

In the research on the combination of optical fiber sensing and triethylamine detection, some teams have developed optical fiber triethylamine room-temperature gas sensors based on a hollow misaligned structure platform, using a CQDs@BiOBr heterojunction as the gas-sensitive layer, with a sensitivity of 3.53 pm/ppm, response/recovery times of 12 s/36 s, and detection limit of 5.67 ppm. This has preliminarily demonstrated the feasibility of optical fiber sensing in TEA detection.

Although certain progress has been made in the field of triethylamine gas detection and optical fiber sensing globally, there are still the following deficiencies: research on optical fiber fluorescence sensors for triethylamine gas is relatively scarce, and the existing achievements are mostly concentrated on the characterization of material intrinsic properties, lacking systematic integration of sensing systems and performance optimization; the uniformity and consistency control of the fabrication process of optical fiber probes (such as pulling coating) remains immature, affecting the batch production and application promotion of devices; most of the current research is at the laboratory verification stage, with a narrow detection concentration range, and is difficult to adapt to the dynamic changes of the concentration of the analyte in actual industrialization and field monitoring. In terms of anti-light interference, anti-chemical corrosion and anti-mechanical damage, further optimization is still needed.

2. The principle of tapered optical fiber evanescent wave sensing

2.1. The formation mechanism of the ephemeral wave

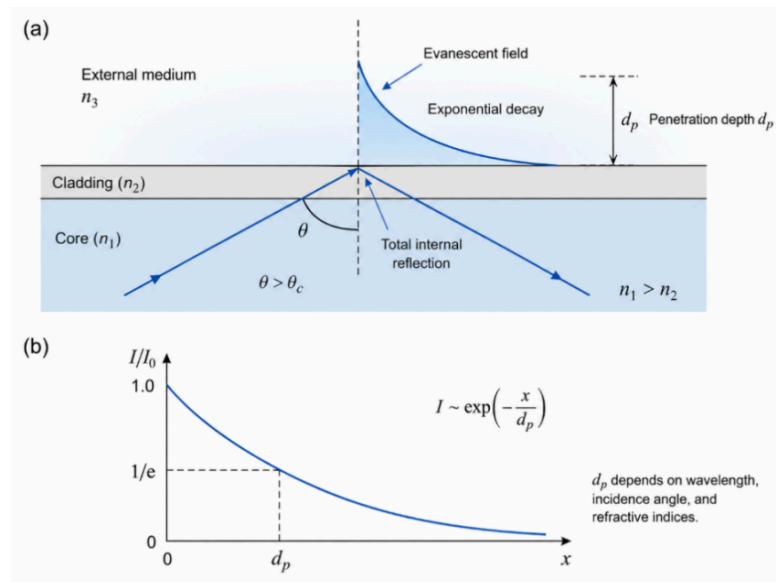


Figure 1. Schematic diagram of the principle of optical fiber evanescent wave sensing. (a)Schematic diagram of the formation and penetration depth of evanescent field under total reflection of optical fibers; (b)Graph showing the exponential attenuation of Transient field intensity with respect to the interface distance

When light propagates in an optical fiber, if the refractive index of the core is greater than that of the cladding and the incident angle is greater than the critical angle, total reflection will occur. From the perspective of geometric optics, the light is completely confined within the core; however, according to the theory of electromagnetic waves, a small portion of the light field will penetrate into the cladding and exhibit an exponential decay along the direction perpendicular to the interface. This portion of the light field is called the evanescent wave, as shown in Figure 1.

2.2. The enhancement effect of conical optical fibers on evanescent fields

In ordinary optical fibers, the light field is mainly confined within the core and has a weak interaction with the external environment. To enhance sensitivity, a conical fiber structure is often adopted. With the gradually decreasing transition zone and the uniform thin-diameter conical waist region, the fiber's ability to confine the light field decreases, and some of the light energy is distributed in the form of evanescent fields on the outer side of the fiber surface. Moreover, as the diameter of the conical waist decreases, the proportion of evanescent field energy and the surface light intensity significantly increase [1-3].

The diameter of the conical waist is a key parameter affecting the intensity of the evanescent field [4]. The smaller the conical waist, the stronger the evanescent wave and the more sufficient the interaction between light and the sensitive material; however, an excessively small diameter will increase the optical transmission loss and reduce the mechanical strength of the optical fiber. Therefore, in actual design, a balance must be achieved among the enhancement of the evanescent field, the transmission loss, and the structural stability. Additionally, the length of the conical region also affects the sensing performance: a longer conical region can provide a larger action area, which is beneficial for enhancing the fluorescence signal, but too long will introduce additional losses and reduce the detection intensity. Reasonable design of the structural parameters of the conical optical fiber is an important step in optimizing the performance of the sensor.

2.3. The sensing mechanism of the fluorescent sensitive layer triggered by the fleeting wave

When the target gas molecules diffuse into the fluorescent sensitive layer, they will undergo physical adsorption, electron transfer or intermolecular interactions with the fluorescent molecules, thereby altering their excitation process. Taking triethylamine as an example, after triethylamine molecules come into contact with IDT-CN, they affect the electron cloud distribution and charge transfer state of the material molecules, enhancing the non-radiative transition channel and causing a decrease in fluorescence intensity, that is, fluorescence quenching occurs. The higher the concentration of triethylamine, the more gas molecules participate in the interaction, and the more significant the quenching degree is. The sensing mechanism of the evanescent wave excites the fluorescent sensitive layer.

Based on the above mechanism, the basic process of the conical fiber evanescent wave sensing can be summarized as follows: The excitation light is transmitted through the optical fiber to the conical area, where the enhanced evanescent field stimulates the surface fluorescent material; the target gas interacts with the sensitive layer, causing a change in the fluorescence signal; finally, the fluorescence intensity is collected by the spectrometer, and the gas response characteristics are analyzed based on the quenching degree. This process realizes the effective conversion of gas concentration into an optical signal, as shown in Figure 3.

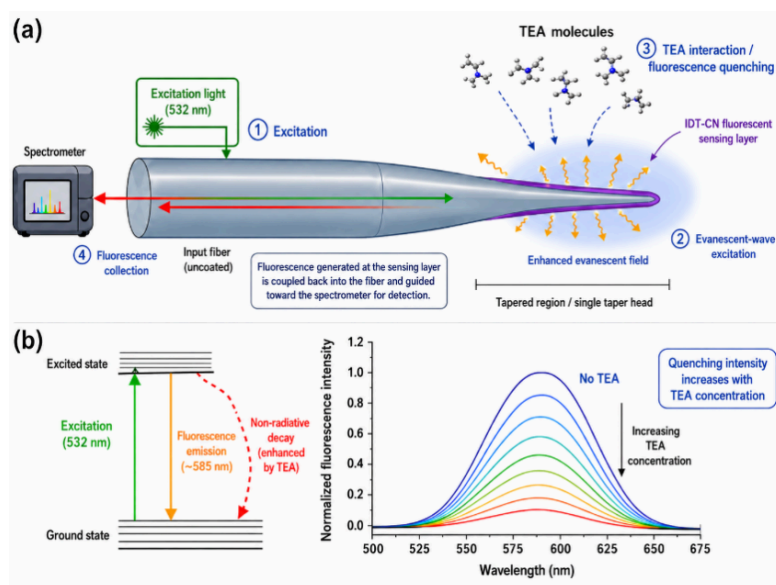


Figure 2. Schematic diagram of single-cone-head optical evanescent wave fluorescence sensing and triethylamine quenching response mechanism. (a) Schematic diagram of the single-cone-head optical fiber fluorescence sensing process and the quenching effect of triethylamine; (b) IDT-CN fluorescence quenching mechanism and fluorescence spectral response at different triethylamine concentrations diagram

3. Screening of Fluorescence-Sensitive materials and response mechanism of IDT-CN

Fluorescent gas sensing is based on the fluorescence emission from fluorescent materials under excitation light. When a target gas (such as triethylamine) interacts with the material, fluorescence quenching (decrease in intensity) occurs through mechanisms such as electron transfer, thereby enabling gas detection [5].

3.1. Optical properties of IDT-CN materials

IDT-CN is an organic semiconductor fluorescent material with a donor-acceptor structure. The intramolecular charge transfer effect is significant, and it easily exhibits fluorescence changes in the presence of amine gases. It is suitable for sensing triethylamine. Optical tests show that the main emission peak of its film in the visible light region is approximately 580 nm, which is convenient for detection with conventional spectrometers and silicon-based detectors, and can reduce system costs. At the same time, the fluorescence intensity of this material remains stable under long-term illumination, and the material exhibits strong resistance to photobleaching, which helps to reduce measurement errors. In addition, IDT-CN still maintains strong fluorescence in the film state and does not show obvious aggregation-induced quenching, making it suitable for loading onto the surface of a conical optical fiber to construct a sensitive layer.

3.2. IDT-CN's fluorescence quenching response to triethylamine

To verify the response ability of IDT-CN to triethylamine, this study conducted fluorescence tests on the IDT-CN film under the action of different concentrations of triethylamine gas. With saturated triethylamine vapor at room temperature as the base gas, high-purity nitrogen gas was used to dilute it successively by factors of 2, 4, 8, 16, and 32, obtaining a series of concentration gradients of test

gases (denoted as saturated and diluted by factors of 2 to 32, respectively). After each gas was introduced, the changes in the fluorescence intensity of the IDT-CN film over time were recorded, as shown in Figure 3.

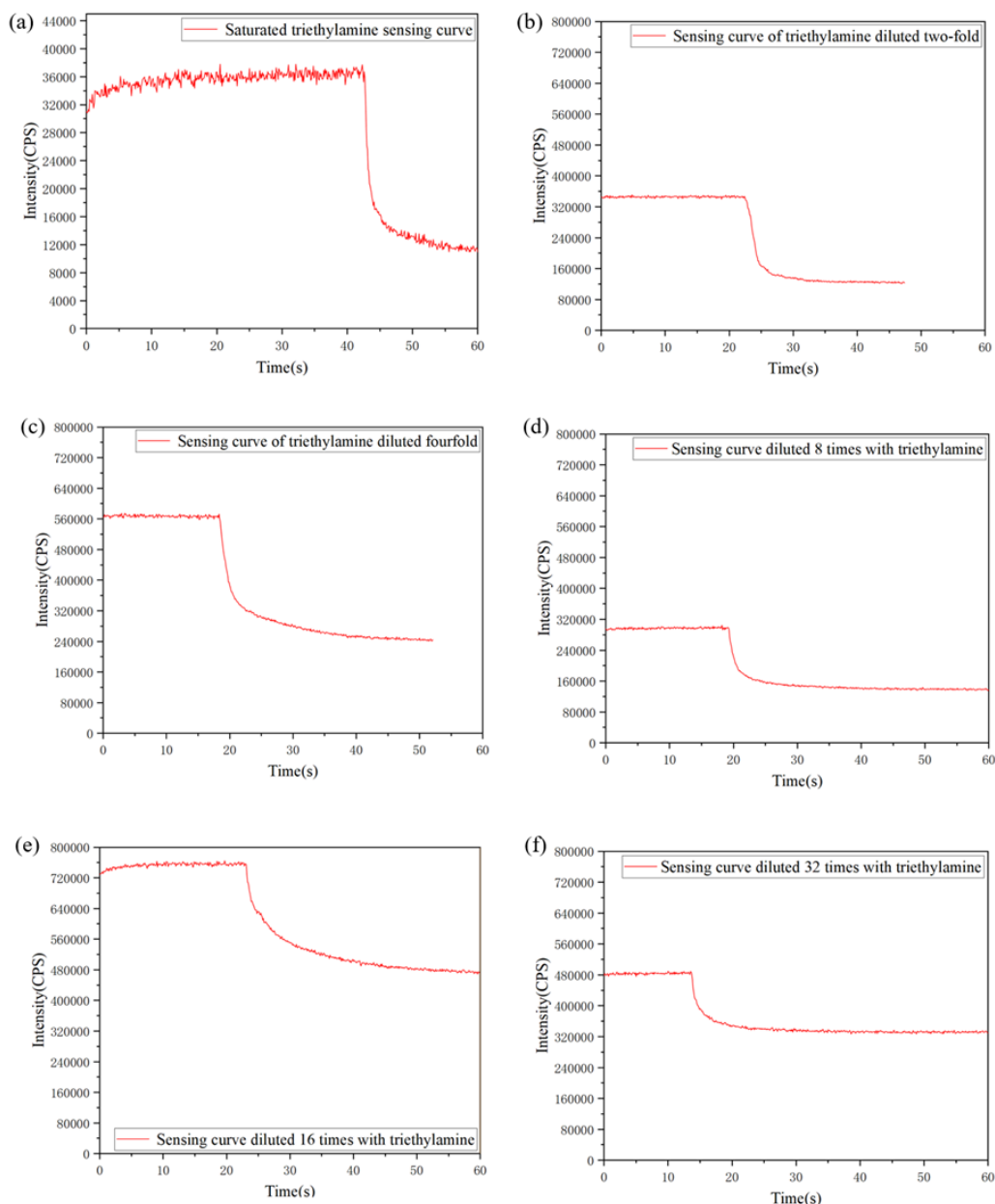


Figure 3. Fluorescence emission spectra of the IDT-CN film under different dilution ratios of triethylamine vapor

The test results show that IDT-CN has a significant fluorescence quenching response to triethylamine gas. Under saturated triethylamine vapor, the fluorescence intensity at 580 nm decreases significantly, with a quenching amplitude of approximately 80%. The quenching amplitudes for dilution by factors of 2, 4, 8, 16, and 32 are 64%, 57.2%, 54%, 38%, and 34%, respectively.

When exposed to saturated triethylamine vapor, the fluorescence intensity of the IDT-CN film rapidly decreased, with a significant quenching extent. As the concentration of triethylamine gas

gradually decreased, the fluorescence quenching degree also decreased accordingly. However, at lower concentrations, a clear response could still be observed. This indicates that IDT-CN has a high sensitivity to triethylamine gas and can effectively reflect changes in the concentration of triethylamine. Therefore, in this paper, IDT-CN was ultimately selected as the core sensitive material for the conical optical fiber triethylamine gas sensor.

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3.3. Analysis of the response mechanism of IDT-CN to triethylamine

The fluorescence response of IDT-CN to triethylamine stems from its intramolecular charge transfer property. IDT-CN contains donor-acceptor units, which undergo charge redistribution upon light excitation, and this process is sensitive to the external molecular environment. As a donating molecule, triethylamine enters the sensitive layer and interacts with IDT-CN, affecting its charge transfer state, resulting in enhanced non-radiative dissipation and decreased fluorescence intensity. The higher the concentration of triethylamine and the more reactive molecules involved, the more obvious the fluorescence quenching becomes; when the concentration decreases, the quenching weakens. Therefore, by measuring the degree of fluorescence quenching, the concentration of triethylamine can be analyzed.

4. Construction and testing of IDT-CN coated conical fiber probe

After determining IDT-CN as the core fluorescent sensitive material for the detection of triethylamine gas, it is necessary to further load it onto the surface of the conical optical fiber to construct a fluorescent optical fiber probe with practical sensing functionality.

4.1. Conical optical fiber surface treatment

The surface condition of the conical optical fiber directly affects the adhesion of the IDT-CN sensitive material. If there are insufficient active sites on the surface, this can lead to uneven distribution of the sensitive layer, weak or unstable fluorescence signals. Therefore, the fiber surface needs to be pre-treated before coating. This study uses the piranha solution (a mixture of concentrated sulfuric acid and hydrogen peroxide in a volume ratio of 7:3) for hydroxylation treatment. This solution has strong oxidizing power and can remove surface organic pollutants and introduce more Si-OH active groups on the fiber, thereby enhancing the surface hydrophilicity and facilitating the uniform adhesion of IDT-CN.

4.2. Coating process of the sensitive layer in IDT-CN

The IDT-CN is loaded onto the surface of the conical optical fiber by the pull-coating method. Firstly, the IDT-CN is dissolved in tetrahydrofuran to prepare a fluorescent material solution; then, the conical optical fiber that has undergone hydroxylation treatment is vertically immersed in the solution, ensuring that the conical area is completely submerged and left to stand to facilitate the full adsorption of the IDT-CN molecules. After immersion, the optical fiber is slowly and uniformly pulled out of the liquid surface, and the solution forms a uniform liquid film on the surface of the optical fiber due to surface tension. After the solvent evaporates, the IDT-CN sensitive layer is obtained. Finally, the coated optical fiber is placed in a dry environment to allow the residual solvent to completely evaporate, and the IDT-CN coated conical optical fiber probe is obtained.

4.3. Fluorescence characterization of IDT-CN coated conical optical fibers

To verify whether IDT-CN has been successfully loaded onto the surface of the conical optical fiber, a fluorescence spectroscopy test was conducted using a 532 nm laser as the excitation source. The excitation light was transmitted through the optical fiber to the conical area, enhancing the evanescent field and exciting the IDT-CN molecules on the surface. The results showed that the coated probe exhibited a distinct fluorescence emission peak near 585 nm, while the uncoated optical fiber did not show this peak. This confirmed that IDT-CN had been successfully loaded and could generate detectable fluorescence under the 532 nm laser. Additionally, the enhanced evanescent field of the conical optical fiber effectively improved the fluorescence excitation efficiency and could return the fluorescence signal along the optical fiber to the detection system, providing a stable signal foundation for the subsequent triethylamine response test.

4.4. Construction of all-fiber fluorescence detection system

In order to effectively collect the fluorescence signals from the IDT-CN coated conical optical fiber probe, this study has built a complete fiber optic fluorescence detection system. This system mainly consists of a 532 nm laser, an optical circulator, a filter group, a conical optical fiber probe, a sealed gas testing chamber, a spectrometer, and a computer.

The use of the circulator can effectively separate the excitation light transmission path and the fluorescence signal reception path, which reduces the interference of excitation light reflection on the fluorescence signal. At the same time, adding a filter group in front of the spectrometer can further filter out the excitation light and stray light, improving the detection signal-to-noise ratio. Through this complete fiber optic detection structure, stable collection of weak fluorescence signals on the surface of the conical optical fiber is achieved.

4.5. Test process for response to triethylamine gas

The experiment employed a fully fiber-optic fluorescence detection system consisting of a 532 nm laser, an optical fiber circulator, a spectrometer, and a sealed test chamber. A conical fiber probe coated with IDT-CN was placed in the test chamber, and the excitation light was transmitted to the probe via the circulator. The excited fluorescence signal returned along the original path and was collected by the spectrometer. After recording the initial fluorescence in air or nitrogen, different concentrations of triethylamine gas (saturated vapor and diluted 2, 4, 8, 16, and 32 times respectively) were successively introduced into the test chamber. The fluorescence intensity changes near 580 nm were monitored in real time.

The experimental results indicated that as the concentration of triethylamine decreased, the fluorescence quenching rate gradually decreased. At saturated triethylamine vapor, the quenching rate reached 96.2%; after dilution by factors of 2, it was 86.7%; after dilution by factors of 4, it dropped to 58.5%; after dilution by factors of 8, 16, and 32, the quenching rates were 54.6%, 53.4%, and 37.7%, respectively. This result verified the response ability of the conical fiber probe coated with IDT-CN to the concentration changes of triethylamine, and the fluorescence quenching degree was positively correlated with the gas concentration.

4.6. Analysis of the response results of triethylamine gas

The experimental results show that the conical optical fiber probe coated with IDT-CN exhibits a significant fluorescence quenching phenomenon when exposed to triethylamine gas. When no triethylamine gas is introduced, the probe has a distinct fluorescence emission peak near 585 nm. However, when triethylamine gas is introduced, the intensity of the fluorescence peak rapidly decreases, indicating that triethylamine molecules have interacted with the IDT-CN sensitive layer and affected the excitation state process of the fluorescent molecules, as shown in Figure 4.

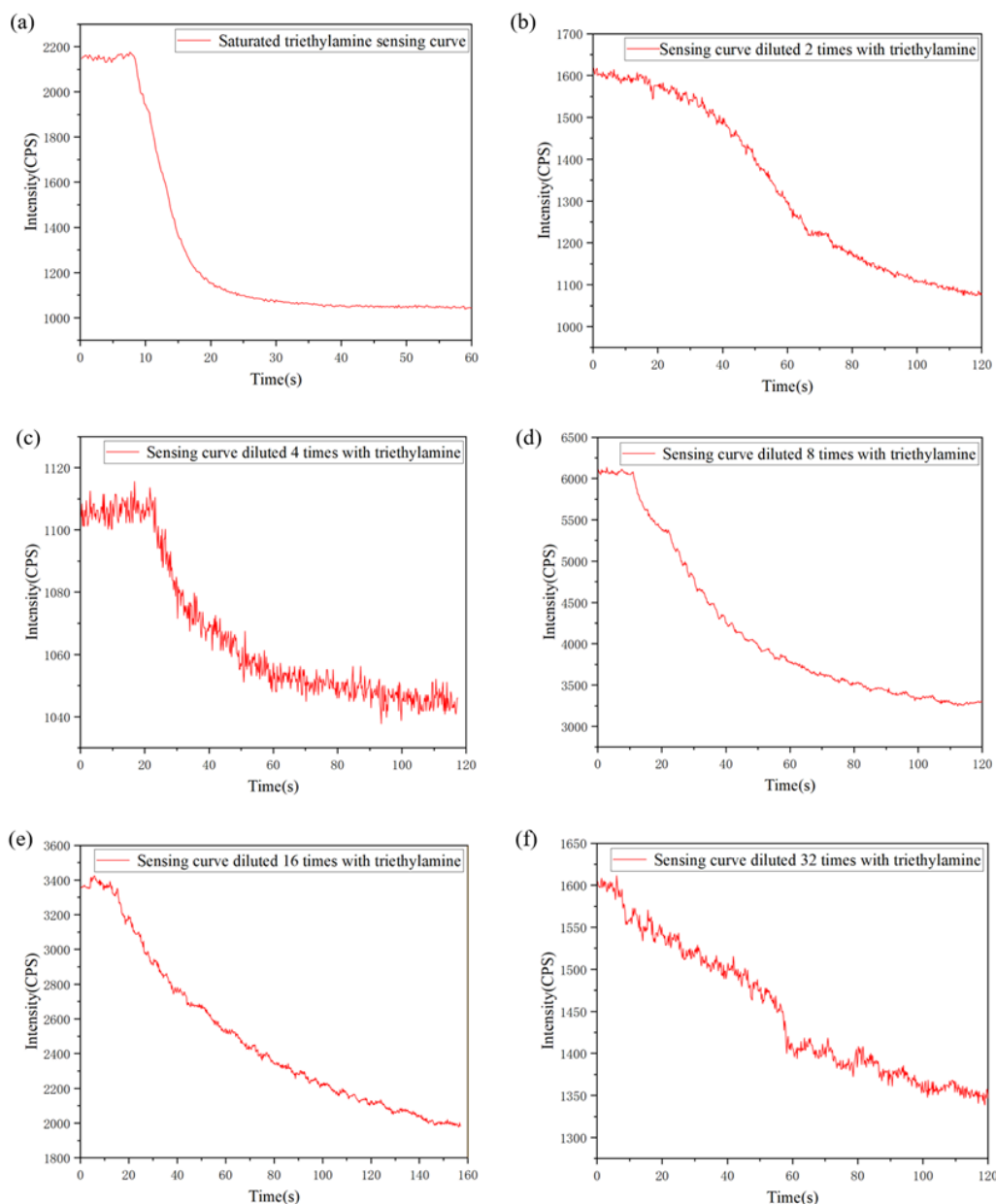


Figure 4. Fluorescence response curve of the conical optical fiber probe coated with IDT-CN under the action of different concentrations of triethylamine gas

Under different concentrations of triethylamine gas, the fluorescence quenching rate of the probe varies significantly. The quenching rate reaches 96.2% under saturated vapor; after dilution by

factors of 2, 4, 8, 16, and 32, the quenching rates are 86.7%, 58.5%, 54.6%, 53.4%, and 37.7% respectively. Overall, as the concentration of triethylamine decreases, the quenching rate shows a downward trend.

This result indicates that the probe responds significantly to triethylamine, and the quenching degree is related to the gas concentration: the higher the concentration, the more gas molecules participate in the reaction, and the more significant the quenching is; as the concentration decreases, the quenching weakens.

Compared with the test results of the IDT-CN film measurements, the quenching trend of the two is basically the same, indicating that the IDT-CN loaded on the fiber surface still maintains good response capability. At the same time, the evanescent wave structure of the conical fiber can effectively excite fluorescence and complete signal transmission and collection, verifying the feasibility of this probe for triethylamine gas detection.

5. Analysis of experimental results

5.1. Analysis of fluorescence quenching results

The experimental results show that the conical optical fiber probe coated with IDT-CN exhibits a significant fluorescence quenching response to triethylamine gas. When no triethylamine is introduced, the probe has a stable fluorescence peak near 585 nm, indicating that IDT-CN has been successfully loaded and the excitation is effective. After introducing triethylamine, the fluorescence intensity significantly decreases.

The test data at different concentrations show that at the saturation triethylamine vapor concentration, the quenching rate reaches 96.2%; after dilution by factors of 2, 4, 8, 16, and 32, the quenching rates are 86.7%, 58.5%, 54.6%, 53.4%, and 37.7% respectively. Overall, the quenching rate decreases with triethylamine concentration, indicating that the probe can respond to the concentration changes. This trend is in line with the fluorescence quenching mechanism: the higher the concentration, the more gas molecules participate in the reaction, and the more obvious the fluorescence quenching is.

Compared with the test results of the IDT-CN film state, the conical optical fiber probe shows a consistent quenching trend, indicating that IDT-CN still maintains good response performance after loading. At the same time, the evanescent field of the conical fiber can effectively excite fluorescence and transmit signals. In conclusion, the combination of the conical fiber structure and the IDT-CN sensitive material for triethylamine gas detection has been verified to be feasible.

5.2 Analysis of Sensing Performance Advantages

The IDT-CN coated conical optical fiber probe constructed in this study has multiple sensing advantages. First, the waist region of the conical fiber can significantly enhance the evanescent field, making the excitation light interact more fully with the surface fluorescent material, thereby improving the fluorescence excitation efficiency and sensing sensitivity. Second, IDT-CN shows a significant fluorescence quenching response to triethylamine, and its quenching amplitude and concentration response characteristics are superior to those of C8-IDTT-IC materials. Moreover, the fluorescence emission is in the visible light range, which is convenient for detection using conventional spectrometers and silicon-based detectors, which is conducive to cost reduction. Third, the all-fiber detection system is compact, resistant to electromagnetic interference, making it suitable for remote detection, and can effectively separate the excitation light and fluorescence signals through an optical circulator, which improves the stability of signal acquisition. In conclusion, the

combination of IDT-CN, conical fiber evanescent wave structure, and all-fiber system provides a solid foundation for achieving miniaturized and highly sensitive triethylamine gas detection.

5.2. Existing problems and improvement directions

Although the experimental results have verified the feasibility of using the IDT-CN coated conical optical fiber probe to detect triethylamine, the current system still has the following shortcomings that need to be addressed.

Firstly, the accuracy of gas concentration preparation needs to be improved. In this study, the saturated vapor stepwise dilution method was adopted, which is simple to operate but is susceptible to factors such as sealing, uniform mixing, and residual gas. In the future, standard gas or a mass flow controller can be used for dynamic mixing to improve the accuracy and stability of concentration control.

Secondly, the stability of the fluorescence signal still needs to be enhanced. The signal from the conical optical fiber probe is weak, and factors such as fiber connection, end face quality, coupling efficiency, laser power, and integration time may cause fluctuations. In the future, the probe position should be fixed, the connection method optimized, the end face processing improved, and the acquisition parameters set reasonably to enhance the system stability.

Finally, the uniformity and repeatability of the sensitive layer need to be improved. Although the pull coating method is simple, the coating thickness and uniformity are difficult to precisely control, and there may be differences among probes. In the future, process parameters such as solution concentration, pulling speed, soaking time, and coating times can be optimized to improve consistency, and repeated tests, cyclic responses, and selectivity tests can be conducted to comprehensively evaluate the repeatability, recovery, selectivity, and long-term stability of the sensor.

6. Conclusion

This paper addresses the demand for detecting triethylamine gas and proposes a fluorescence sensing method based on the IDT-CN sensitive film and the evanescent wave enhancement effect of the conical optical fiber. Theoretical analysis and experiments show that the conical optical fiber can effectively enhance the surface evanescent field and improve fluorescence excitation efficiency. Through comparison of the two materials, C8-IDTT-IC and IDT-CN, it was found that IDT-CN has a more obvious fluorescence quenching response to triethylamine, so it was selected as the core sensitive material.

In terms of experiments, the surface of the conical optical fiber was hydroxylated using the piranha solution, and IDT-CN was loaded onto the fiber surface by the pull-off coating method, successfully preparing an IDT-CN-coated conical optical fiber probe. At the same time, a full-fiber fluorescence detection system composed of a 532 nm laser, an optical fiber circulator, a filter, a spectrometer, and a sealed test chamber was built to collect and analyze the fluorescence signal.

The triethylamine response test results show that the fluorescence quenching rate of this probe reaches 96.2% under saturated triethylamine vapor; as the gas is gradually diluted, the quenching rate generally decreases, indicating that the probe has a good response ability to the change in triethylamine concentration. Compared with those from the IDT-CN film measurements, the response trends of both are consistent, indicating that IDT-CN still maintains excellent sensing performance after loading.

In conclusion, this study demonstrates the feasibility of combining the evanescent wave structure of the conical optical fiber and the IDT-CN sensitive material for triethylamine gas detection, providing an experimental basis and reference for the subsequent development of miniaturized, high-sensitivity, and remotely operable fiber-optic fluorescence gas sensors.

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