Effective detection of ZnO in nicotine using butterfly wing scales

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ABSTRACT
This study aimed to elucidate the optical functions of naturally butterfly wing scales via precise control of morphology as an effective photonic sensor and confirm the content of metal oxide nanoparticles in surrounding nicotine. Metal oxide nanoparticles mixed with nicotine were deposited on the wing scales through the spin-coating method and hence investigated using optical microscopy and spectroscopy. Experimental results demonstrated that absorption intensities of ZnO and TiO2 mixed with nicotine on Danaus genutia were remarkably enhanced. Due to the relatively high concentration of zinc found in e-cigarette aerosol, the intensity of ZnO/nicotine modelled as aerosol adsorption on Danaus genutia, further held a certain linear relationship with the concentration of ZnO. The limit of detection of ZnO was as low as 1 nM. The working mechanism of our sensor was explained through the molecular adsorption after H-bond formation of ZnO/nicotine molecules as high-index materials on the wing scales of Danaus genutia without aggregation. This photonic sensor is an alternative to the present-day methods for the rapid test of ZnO content, which is very simple without complicated instrumentation. Furthermore, our method might become a starting point for the advancement of portable instruments for onsite ZnO detection.

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Introduction
Motivations
Lung cancer is the second most common cancer, and the statistics in the US for 2022 include about 236,740 new cases and 131,180 deaths [1]. A person who is struggling with nicotine addiction shows a synergistic effect on the pathogenesis of lung cancer. The contribution of metallic coils and a trace level of nicotine in e-cigarette aerosol are thought to deliver metal-oxide/nicotine via to the lung without burning tobacco. Ultraviolet radiation produced by metal nanoparticles strongly excites nicotine and damages DNA (genes) in cells. Despite the available treatment strategies (surgery, radiotherapy, and chemotherapy) that have been developed to detect these trace elements at an initial sign of malignancy, an optical detection scheme is considered as one of the potential solutions to investigate the target analyte, so as to lower the cancer mortality rate. Therefore, the development of highly sensitive tumour screening tests would motivate further studies of metal sensing performances in e-cigarette aerosol.

Literature reviews
Butterfly wing-aided markers have drawn tremendous attention for sensor applications as the intensity of colourisation from butterfly wing architectures could be modified via the surrounding medium. For example, Morpho and Polyommatini butterflies showed anisotropic optical responses to thermal expansion [2]. Papillon junonia butterfly was used to detect gasoline contamination [3]. These studies led to the development of a new generation of bio-template methods. Recently, the optical response in the UV-visible wavelength regime due to the anisotropic characteristics of inorganic materials on the butterfly wing scales mostly offers unique information about vapour and liquid identification (Table 1) [4–9]. However, a promising optical enhancement yielded by photonic crystal microstructures composed of pristine butterfly wing scales has been a little exploited with a proof-of-concept experiment of the solid-detection scheme by monitoring the other key parameters, such as aspect ratio and Fabry-Pérot cavity.

Hypothesis
Colour patterns of the butterfly wing scales originate either from chemical pigments or scale textures [10]. Pigmentary colour is a result of the presence of pigments in the structures that interact with the incident light. Typical scale structures include so-called main ridges, ribs, struts, etc. and they work together to effectively interfere, scatter, and diffract the incident light [11]. The intensity of colourisation is not only
dependent on the ridge height, periodicity, and ridge gap of the scales, but also on the refractive index, angle, and wavelength of action of the incident light on the scales.

The aforementioned quasi-periodic microstructures that build a photonic crystal of butterfly wing scales represent the dominant way of structure-enhanced optical properties; however, their structures tend to show chordwise and spanwise deformations [12]. Such details are likely to be important in optical sensing. Using butterfly wing scales as a new platform for inorganic materials of interest via physical adsorption might overcome these drawbacks. In this respect, microstructures consisting of biological architectures might provide quantitative spectral results for the target analyte. The optical resonance behaviour of photonic crystal gratings is highly sensitive to localised changes in binding interactions on their surfaces, resulting in a shift of the resonance peak wavelength, which is proportional to the concentration of the target analyte. This makes them suitable for sensing platforms for multiple applications of chemical/environmental/bio-sensing. In addition, they generate ecologically friendly optical sensing devices. The organic constituents in the butterfly wing scales can be removed by annealing them to 500–800°C for 3–6 h in an atmospheric environment so that the organic wing scales are burned out in the presence of oxygen.

**Contributions**

This study aimed to expand the practical application of the proposed photonic microstructures using butterfly wing scales that act as optical enhancers for the detection of small signalling metal-oxide/nicotine originating from e-cigarette aerosol, thereby lowering the limit of detection of the sensing device. We showed that the absorbance and diffraction pattern at a far-field depended on the pigmentation and periodic ridge-to-lamella structures of the wing scales. Alternation of the surrounding medium on the wing scales as a refractive index sensing was carried out to produce a visual response with refractive index variation, offering a new direction for the design and fabrication of high-performance sensors in the future. In this regard, the selectivity and sensitivity of the target analyte were determined using a different type of metal oxide nanoparticles mixed with nicotine in liquid form, as an important factor for the development and severity of human lung cancer. They were selected for model monitoring, so that prompt cancer treatment is curable. The sensing performance of butterfly photonic structures was explained. The dose-response curve for the target sensing event was also discussed.

**Materials and methods**

**Materials**

Zinc oxide (ZnO, φ = 50 ± 5 nm), copper oxide (CuO, φ = 50 ± 5 nm), and titanium dioxide nanopowders (TiO₂, φ = 100 ± 5 nm), ethanol, and polymethyl methacrylate (PMMA) were purchased from Sigma-Aldrich, USA. Dimethyl sulfoxide (DMSO) was purchased from Merck, USA. Butterfly samples were obtained from the Insect Zoo and Museum (Table 2). The butterfly wing scales showed the brown-to-black or white backgrounds with isolated bright coloured patterns. Monochromatic light sources, namely green laser diode (520 nm, 0.9 mW, Ø11 mm, model: PL203) and red laser diode (635 nm, 0.9 mW, Ø11 mm, model: PL204) were purchased from Thorlabs GmbH, Germany.

**Butterfly wing preparation**

Cutting and positioning the butterfly samples were important when exploring the inner structure of the butterfly wing scales, which were prepared as follows: (1) The butterfly wing scales were placed on the sample holder using a rotational stage of the optical microscope to achieve a good image. (2) The hydrophobic wing surface was carefully cut perpendicular to the ridges in a dry air environment, using a razor blade to obtain a small section of 10 × 10 mm²; (3) The sliced wing scales were immersed in ethanol for 1 h to remove impurities adhering to the wing surface; (4) the sliced wing scales were picked up by a glass slide, followed by rinsing with deionised water twice, prior to drying in the air for 1 h.

**Dose-dependent toxic effect of metals in nicotine**

Zinc oxide stock solution was diluted with deionised water to achieve final concentrations of 10, 12, 14, 16, and 18 nM (Table 2). In order to test the selectivity of metal-oxide/nicotine adsorption on the butterfly wing scales, different types of metal

| Materials | Fabrication methods | LOD of target analytes | References |
|-----------|---------------------|------------------------|------------|
| Ag-Au on Euploea mulicer | Wet chemical | Rhodamine 6 G = 1 nM | [4] |
| Pd on Morpho sulkowskyi | Physical vapour deposition | Hydrogen = 5 mM | [5] |
| Ag on Hoetera piera | Magnetron sputtering | Crystal violet = 10 μM | [6] |
| SiO₂ on Morpho didius | Plasma | Thrombin = 0.2 pM | [7] |
| TiO₂ on Princess paris | Sintering | Acetone = 0.1 mM | [8] |
| Ag on Sasakia charonda | Wet chemical | Rhodamine 6 G = 10 μM | [9] |

LOD: Limit of detection.
oxide nanoparticles including CuO and TiO₂ were used in comparison to ZnO. Concentrations of each metal oxide nanoparticles were kept at the level of 16 nM. They were then dispersed in an ethanolic nicotine dosage of 1.60% (16 mg), similar to the nicotine dosage in a traditional cigarette. PMMA powder (200 mg) was dissolved in DMSO (1 ml). Then, 1 ml of the clear solution was blended with metal-oxide/nicotine. After that, the pre-treated butterfly wing scales were spread with aliquots of metal-oxide/nicotine as an aerosol medium of about 50 µL into the PMMA matrix, using the spin coating method (3500 rpm, 60 s). The refractive index of 80–200 nm PMMA at 450 nm was 1.50, which was comparable to the butterfly wing scales (n = 1.56) [10]. The samples were then dried in air at room temperature for 1 h to ensure the adsorption-desorption equilibrium of metal-oxide/nicotine on the sample. As the solid and liquid molecules were immobilised all over the sample, discolouration of the wing scales was observed immediately. Because the uniformity in sample position might reduce the sensing performance, microscopic imaging before sense was required to identify the best wing scales with good uniformity. The control samples were native metal oxide, metal-oxide/nicotine, and pristine wing scales exposed on a glass slide for comparison. Digital images of the specimens as parts of the butterfly wing scales before and after treatment with metal-oxide/nicotine were recorded. After that, the butterfly wing scales exposed to metal-oxide/nicotine deposition were verified through scanning electron microscopy (SEM) and Fourier-transform infra-red spectroscopy (FTIR). Absorbance was detected by UV-Visible spectroscopy.

**Microscopic measurements**

The surface morphology of metal-oxide/nicotine deposition on the butterfly wing scales was imaged using SEM at a normal angle (JOEL JSM-IT500HR, Japan). The accelerating voltage used in SEM for biological tissues (2–12 kV) was much lower than that for metallic and solid samples (30–60 kV) because a large voltage caused a contraction of the wing structures and deformation. It was preferable to use a low voltage of 10 kV with a working distance of 21.4 mm and a small spot, although higher voltages gave a better resolution. The SEM images (250,000× magnification) were captured to reveal the self-assembly of typical chitin-microstructure arrays, making up the wing patterns.

**Optical measurements**

For absorbance measurements (Figure 1), a white light beam emitted from a broadband tungsten light source (200–1100 nm), passing through the fibre optic, and then focussed at a normal angle to the area of interest. The light was collected and guided to a fibre-optic spectrometer (Avantes, Netherlands). The absorbance of the prepared samples under a normal incident light was measured. The spectrum of PMMA on the glass slide was recorded to eliminate the background signal. The spectra of native metal oxide and metal-oxide/nicotine on a glass slide were used as a control signal. The spectra of butterfly wing scales exposed to metal-oxide/nicotine deposition were used as a sampled signal. As C-, H-, and O-based organic skeleton structures of the butterfly wing scales, acquisition times were kept as short as possible to reduce heating, which might cause sample damage. The integration time for a single spectrum was 300 ms, with spectra averaged over 10 acquisitions. All-optical experiments were carried out in the dark at room temperature (25 °C) to avoid stray light from the surrounding environment. We determined the absorbance versus the molar concentration of metal oxide on the butterfly wing scales. From the slope of the linear plot (a), we obtained the limit of detection (LOD) of metal oxide from the following equation [13]

\[
LOD = k \frac{SD}{\sqrt{n}} + \frac{R^2}{12}
\]

where k is uncertainty constant (k = 3), SD is the standard deviation of the blank (SD = 0.01), n is the number of experimental runs, and R is instrumentation readout (R = 0.01) [13]. The optical diffraction of metal-oxide/nicotine on the butterfly wing scales was experimentally examined with monochromatic (green and red) light under normal illumination. Far-field diffracted light was observed on an image-screen setup using white A4 paper. Diffraction patterns were captured using a digital camera. The diffraction intensity was measured using an optical power metre (Thorlabs Elliptec GmbH, PM100D, Germany).

**Statistical analysis**

All measurements exhibited in tables and figures as mean ± standard deviation were obtained from triplicate experiments. Data were analysed using the graphical and statistical modelling package “Origin5.0,” differences were tested by ANOVA (analysis of variance), and significance was disclosed at p < .005.

**Results**

**Sample images**

Optical microscopic images of the three different types of butterfly wing scales before and after metal-oxide/nicotine deposition are shown in Figure 2. *Troides aeacus* (Sample# A5) shows vivid yellow-to-green wing scales with round edge shapes. *Danaus genutia* (Sample# B5) shows vivid orange wing scales with toothed edge shapes. *Morpho didius* (Sample# C5) shows vivid blue wing scales with round edge shapes. The magnified SEM images of all butterfly wing scales appear to be identical. The wing scales construct an array of longitudinal and parallel rows of ridges, which constitute a grating component. They are tilted at an angle kept at a distance from each other, connected by a series of transversal cross-ribs protruding from the sides of the ridges. The cross-ribs are interconnected to each other. Microlibs

| Sample# | Butterfly wing scales | ZnO [nM] | Nicotine, NT [%] |
|---------|------------------------|---------|----------------|
| A0, A1, A2, A3, A4, A5 Troides aeacus | 0, 10,12,14,16,18 | 1.60 |
| B0, B1, B2, B3, B4, B5 Danaus genutia | 0, 10,12,14,16,18 | 1.60 |
| C0, C1, C2, C3, C4, C5 Morpho didius | 0, 10,12,14,16,18 | 1.60 |
located on both sides of the ridges scatters the incident light. The periodic-rectangular structures between the ridges and micro ribs are considered to provide a large surface area for the binding interaction between metal-oxide/nicotine molecules and incident light. The area framed by adjacent ridges and cross-ribs, so-called windows in a rectangular porous network structure, could be captured with metal-oxide/nicotine molecules as an analyte model during metal-oxide/nicotine deposition. The dimensional parameters of the three different types of butterfly wing scales are listed in Table 3.

**Optical absorption**

Absorption is considered as the main characteristics that evaluate the sensing performance of metal oxide nanoparticles mixed with nicotine on the butterfly wing scales. We first measure the absorption spectra for the prepared samples, using a UV-Vis spectrometer. Figure 3 displays the absorption peak of CuO (with a bandgap of 4.1 eV [14]), ZnO (with a bandgap of 3.8 eV [15]), and TiO$_2$ nanoparticles (with a bandgap of 3.6 eV [15]) mixed with nicotine on Danaus genutia at the central wavelength 440, 460, and 465 nm, respectively. In all metal oxide nanoparticles mixed with nicotine on Danaus genutia, the absorption peak values are slightly shifted as compared with Danaus genutia, due to metal oxide nanoparticles are infiltrated in Danaus genutia. It is found that TiO$_2$ and ZnO mixed with nicotine represent very well a good sensing system, owing to their high selectivity and selectivity with respect to the effective surface areas of Danaus genutia. Since zinc has been found in relatively
high concentrations of e-cigarette aerosol [16], it turns out to be a good candidate for reliable detection of ZnO on the butterfly wing scales.

The absorbance of ZnO/nicotine on the butterfly wing scales seen in Figure 4 is proportional to the concentration of ZnO. Ommochrome pigment is suggested to determine the colour of Troides aeacus [3], whereas melanin is suggested to differentiate the colour of Morpho didius [17–19]. The order of increasing absorbance of ZnO/nicotine coated on the butterfly wing scales is: Morpho didius (3.5) > Danaus genutia (3.2) > Troides aeacus (2.8). The absorbance was approximately six times higher than those of native ZnO (0.58) and ZnO/nicotine (0.65). The order of redshift of ZnO/nicotine with the concentration range of ZnO coated on the butterfly wing scales is as follows: Danaus genutia (425–487 nm) > Morpho didius (430–455 nm) > Troides aeacus (456–460 nm).

**FTIR data**

Figure 5 shows FTIR spectra in the wavenumber range of 400–4000 cm\(^{-1}\) for butterfly wing scales before and after deposition of each examined metal oxide nanoparticles mixed with nicotine. The concentrations of all metal oxide nanoparticles are the same (16 nM). Interestingly, melanin shows a main peak at 1625 cm\(^{-1}\) (C = C) [17–19].

**Optical diffraction**

The diffraction pattern of Morpho didius is unobservable because the blue wing scales containing melanin seen in FTIR data tend to absorb light from the ultraviolet to near-infrared spectrum [17–19]. In Figure 6, the diffraction patterns of Troides aeacus and Danaus genutia are observed with monochromatic green (520 nm) and red (635 nm) light illuminations at the front side of the wing scales. For normal illumination, periodic grating structures could produce arrays of periodic spots. The diffraction envelope consists of a high-intensity non-diffracted zero-order (\(m = 0\)) and low intensity of the first diffraction order (\(n = 1\)). The distance between the zero-order maximum and the first diffraction order at the far-field intensity distribution is calculated for the green and red-light illuminations to be 30 and 45 mm, respectively. The angles of incident light by which the green and red-light wave bends are therefore determined to be 15° and 20°, respectively. The maximum and minimum diffraction intensities with respect to the non-diffracted zero-order indicate that the diffraction intensity of the green light is higher than that of the red light.

**Discussion**

In Figure 2, when the treated butterfly wing scales undergo without thermal processing, the butterfly wing structures are not broken, and thus almost unchanged, are seen in the dimensions of the wing scales and their components. The properly arranged butterfly wing scales are not disrupted, whereas periodicity is maintained. The spin coating process causes the well-ordered structures to create a long-range ordered structure, owing to the specific interactions between the wing components and metal-oxide/nicotine molecules. As shown in Table 3, the ratio of ridge height and periodicity is never larger than 0.5, indicating that the periodicity is never larger than double the ridge height. This point assists in dry self-cleaning and improves aerodynamics. The lowest value (0.15) is found in Morpho didius [25]. These ratios influence the adherence of ZnO/nicotine molecules. As the aspect ratio is well below 0.5, ZnO/nicotine could stick between the two ridges. The effective surface areas of the butterfly wing scales that facilitate mass transport easily provide efficient surface accessibility, while maintaining the equilibrium condensation of ZnO/nicotine molecules. The butterfly wing scales exposed with ZnO/nicotine clearly show a partial

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**Table 3. Structural parameters of typical chitin-microstructure arrays in three different types of butterfly wing scales calculated from SEM micrographs.**

| Parameter# | Troides aeacus (dorsal-hindwing) | Danaus genutia (ventral-forewing) | Morpho didius (dorsal-forewing) |
|------------|----------------------------------|----------------------------------|----------------------------------|
| 1: Height of ridge (µm) | 0.79 ± 0.01 | 0.41 ± 0.04 | 0.34 ± 0.02 |
| 2: Periodicity (µm) | 1.91 ± 0.03 | 2.07 ± 0.03 | 2.24 ± 0.04 |
| Aspect ratio = (1)/(2) | 0.27 ± 0.01 | 0.20 ± 0.01 | 0.15 ± 0.03 |
| Gap between ridge | 1.30 ± 0.02 | 1.47 ± 0.03 | 1.24 ± 0.01 |
| Fabry-Pérot cavity (µm²) | – | 0.51 ± 0.04 × 1.14 ± 0.03 | 1.05 ± 0.01 × 1.66 ± 0.02 |
Figure 4. (a) Absorbance of native ZnO and ZnO/nicotine; (b–d) Absorbance of the butterfly wing scales before and after ZnO/nicotine deposition. Dash line is the guideline to the eyes.

Figure 5. FTIR spectra of butterfly wing scales before and after ZnO/nicotine deposition.
bleaching influence (Figure 2), that is, partial extraction of the short-wavelength absorbing pigment so that the absorbance of the partially bleached wing scales provides a much more refined picture. The absorbance is still high because the excitation light is absorbed by the ommochrome pigment in addition to melanin [25].

In Figure 4, the redshift of absorbance is detectable after the growth of ZnO/nicotine molecules over the butterfly wing scales. Upon contact with ZnO/nicotine, the peak position is a red shift by 4, 15, and 62 nm in the case of ZnO/nicotine-coated *Troides aeacus*, *Morpho didius*, and *Danaus genutia*, respectively, for the following reasons. First, when the wing scales have no periodic-rectangular structures between the ridges and micro ribs, light scattering is incoherent or random, resulting in a non-shift or tiny shift in the absorbance of *Troides aeacus*. The lamella tilt angles are approximately 9°, 15°, and 25° for *Morpho didius* [26,27], *Danaus genutia*, and *Troides aeacus* [28], respectively. When the angle of incident light is well away from grazing incidence, the light scattered by this structure becomes weak (yellow pigment). However, when the angle of incident light is near the grazing incidence, the displayed colour is green. On the other hand, light with a certain wavelength corresponding to the periodic-rectangular structures is trapped inside the longitudinal-parallel ridge-grating structures when the wing structures have spatial periodicity. When lamella slabs on the two sides of the ridges are random offsets, the direction of the incident light is split and considered as a waveguide, producing a definite colour shift of the absorbance of *Morpho didius* and *Danaus genutia*. However, the larger random offsets in *Morpho didius* play a dominant role in broadening the absorbance. The absorbed incident light, from ultraviolet to near-infra-red radiation, might be converted into heat energy. The female butterflies could hence get more energy storage, to be used for breeding, from sunlight than male butterflies. Second, ZnO/nicotine incorporation further fills in the space between the cross-ridges, introducing a gradual refractive index profile at the air-chitin interface and hence offers a smaller redshift of the absorbance of *Troides aeacus* and *Morpho didius* [2,3].

The principal maximum in diffraction is explained as \(d \sin \theta = n \lambda\), where \(d\) is the gap between the ridges, \(\theta\) is the angle at which the light wave bends, \(n\) is an integer, and \(\lambda\) is the wavelength of the incident light. Therefore, the type and intensity of the observed colour are defined by the ridge gap. Because the ridge gap of the butterfly wing scales is in the range of 1200–1500 nm as shown in Table 3, the incident beam of light could be scattered in various directions by the ridges as an effective diffraction grating. A gap between the ridges are 1.30, 1.47, and 1.24 for *Troides aeacus*, *Danaus genutia*, and *Morpho didius*, respectively (Table 3). Therefore, we confirm that the higher value (1.47) is accountable for the photonic structures of *Danaus genutia*, while the two smaller values (1.24 and 1.30) are due to simple light absorption by ommochrome pigment in the groove of *Troides aeacus* and by melanin of *Morpho didius* [3,17–19].

In Figure 6, the distances between the second diffraction minimum and the central maximum in the far-field diffraction patterns are calculated for green (520 nm) and red (635 nm) light illuminations to be 30 and 45 mm, respectively. The distance increases as the wavelength increases, following Bragg’s law. The electric field intensity distribution of the diffraction pattern shows an asymmetrical shape because the longitudinal ridges aligned at 9°–25° with respect to the
horizontal plane further cause an electric field-dependent shape anisotropy, causing a slight angle dependence of the light intensity. If the diffraction efficiency is defined as the ratio between the diffraction intensity and incident light intensity and expressed as a percentage, it is found that the maximum diffraction efficiency of Danaus genutia is the best through the green light under normal illumination. Therefore, Danaus genutia is suggested to be a good (wavelength-selective) diffraction grating. The optical properties of such diffraction gratings have diverse applications, such as spectroscopy, wavelength filters, tuneable lasers, displays, holography, and security applications. In the absorbance measurement setup, the input beam is incident perpendicular to the butterfly wing surface so that it is possibly propagating along the ridge-to-lamella direction and fully interacts with the Fabry-Pérot cavity in the window-like quasi-periodic structures of Danaus genutia. A well-organised Fabry-Pérot resonance existing in each window is described as $L = \lambda m / 2n$, where $L$ is the resonance Fabry-Pérot cavity length corresponding to the size scale of each window (1140 nm), $\lambda$ is the resonant wavelength (425–487 nm), $m$ is a positive integer, and $n$ is the refractive index ($n = 1$). We obtain m integers of approximately 5. Owing to the quasi-periodic structures of these wing scales, coupling among the FabryPérot cavity mode makes it a valuable tool to enhance the peak intensity of some particular eigenmodes [29].

Since Danaus genutia shows dual functions in terms of absorbance and diffraction in comparison to that of the other two, the typical architecture of Danaus genutia is favourable for sensing purposes as a prototype architecture for further sensing applications. Considering the concentration of ZnO/nicotine coated on Danaus genutia, the absorbance as a function of ZnO concentration is strikingly different, as plotted in Figure 7, showing an obvious positive correlation with the concentration range of ZnO. Therefore, the limit of detection of ZnO/nicotine, which served as a model of the target analyte, was sensitively distinguished, owing to the butterfly photonic structures. The absorbance of ZnO/nicotine on Danaus genutia was found to be approximately 1 nM. The limit of detection of ZnO/nicotine based on the Danaus genutia sensor is somewhat similar to those typical for biologically inspired sensors associated with the literature under specific requirements for chemical and thermal treatments [4], for which the loading content is close to 1 nM. However, the metal concentration level corresponding to our detection limit is still higher than that of SiO2 on Morpho didius for the detection of thrombin [7]. This demonstrates the viability and practical importance of the simple technique suggested in the present study.

This study has two limitations. First, ZnO/nicotine formation might not be perfect. Some of the untreated wing scales might have been left with ZnO or nicotine molecules. The volume variation of the refractive index of ZnO/nicotine influences these whole structures and, in turn, might change the light absorption. We focus on the cover wing and completely ignored the impact of the ground wing. Therefore, the measurement setup is unable to collect all the scattered light from the actual wing scales.

Conclusions

The purpose of this study was to demonstrate the application of hierarchical structures of butterfly wing scales as an attractive candidate for sensing the performance of metal oxide nanoparticles in e-cigarette aerosol. Metal oxide nanoparticles mixed with nicotine on different butterfly wing scales (Troides aeacus, Morpho didius, and Danaus genutia) were fabricated using a spin-coating method within 60 s. The modified microstructures were observed by scanning electron microscopy and Fourier-transform infrared spectroscopy, whereas their absorbance was detected using a UV-Vis spectrometer. If compared with the examined metal oxide nanoparticles (CuO, ZnO, and TiO2) at equivalent concentration, it was found that the surface of butterfly wing scales modified by ZnO/nicotine was suitable for further detection of ZnO mainly present in e-cigarette aerosol. Asymmetry and dimensional variation of ridge-to-lamella structures and ZnO/nicotine inclusion contributed to the changes in the absorbance and diffraction. ZnO/nicotine on the wing scales exhibited a significantly higher optical response than the native ZnO/nicotine. It was also found that the colour of the butterfly wing scales covered by ZnO/nicotine was slightly brighter than that of the pristine wing scales, as indicated by the naked eye. The concentration of ZnO/nicotine distributed on Danaus genutia was sensitively distinguished, owing to the butterfly photonic structures. The absorbance of ZnO/nicotine on Danaus genutia, was able to determine the limit of detection of 1 nM ZnO. The key characteristic of the modified microstructures on analyte sensitivity was the spontaneous localisation of ZnO and nicotine molecules into the reactive area of butterfly wing scales, providing more efficient surface accessibility, leading to improved mass transport properties of ZnO/nicotine, which served as a model of the target analyte. This point yielded an excellent enhancement of the optical signal. Due to the high selectivity and sensitivity of ZnO/nicotine on the butterfly wing scales, the photonic
sensor developed in this work could be used as a good metal-ion detector for photonic and biomedical applications.

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Disclosure statement
The authors declare no competing financial interests.

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Author contributions
Thanachai Changcharoen, Thidsanu Apiphatnaphakul and Wasupon Watjanavarreerat participated in the research design, data collection, data analysis, and wrote the manuscript. Kitsakorn Locharoenrat performed the research design, data analysis, research summary and recommendation, as well as wrote the manuscript. All authors read and approved the final manuscript.

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Data availability statement
All data and material used to support the findings of this study are included within the article.

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