Spectrometer-free Optical Hydrogen Sensing Based on Fano-like Spatial Distribution of Transmission in a Metal–Insulator–Metal Plasmonic Doppler Grating

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Optical nanosensors are promising for hydrogen sensing because they are small, free from spark generation, and feasible for remote optical readout. Conventional optical nanosensors require broadband excitation and spectrometers, rendering the devices bulky and complex. An alternative is spatial intensity-based optical sensing, which only requires an imaging system and a smartly designed platform to report the spatial distribution of analytical optical signals. Here, a spatial intensity-based hydrogen sensing platform is presented based on Fano-like spatial distribution of the transmission in a Pd-Al₂O₃-Au metal-insulator-metal plasmonic Doppler grating (MIM-PDG). The MIM-PDG manifests the Fano resonance as an asymmetric spatial transmission intensity profile. The absorption of hydrogen changes the spatial Fano-like transmission profiles, which can be analyzed with a “spatial” Fano resonance model and the extracted Fano resonance parameters can be used to establish analytical calibration lines. While gratings sensitive to hydrogen absorption are suitable for hydrogen sensing, hydrogen insensitive gratings are also found, which provide an unperturbed reference signal and may find applications in nanophotonic devices that require a stable optical response under fluctuating hydrogen atmosphere. The MIM-PDG platform is a spectrometer-free and intensity-based optical sensor that requires only an imaging system, making it promising for cellphone-based optical sensing applications.

1. Introduction

Hydrogen has been widely used as a coolant and raw material in the semiconductor industry and food industry.¹ As a carbon-free energy carrier with high energy density, hydrogen is the most promising clean-burning fuel resource for the future.² However, its properties of odorless, colorless, high flammable, wide explosive range (4–75 Vol.%), and low spark ignition energy (0.02 mJ) also arise critical safety concerns due to potential explosion risks.³ Safety protocol implementation and real-time monitoring are essential for its application. Sensitive, accurate, and fast leakage detection, especially for detecting hydrogen below the explosive limit (<4%), is critical.

Various hydrogen sensing strategies have been proposed, including microelectromechanical,⁴ catalytic,⁵ thermal,⁶ electrochemical,⁷ mechanical,⁸ optical,⁹ and acoustic detection schemes. The core element for all these sensing systems is the hydrogen sensitive materials, such as metal oxides (In₂O₃,¹¹ ZnO,¹² TiO₂,¹³ and W₁₈O₄₉¹⁴) and hydride-forming metals (Pd,¹⁵ Mg,¹⁶ Y¹⁷ alloys¹⁸). Among various sensing materials, metal oxides are less applicable because they require a high working temperature of over 400 °C to maintain optimal sensitivity. Therefore, hydride-forming metals, which can work at room temperature with high sensitivity and selectivity, have been commonly used in optical hydrogen sensors. In particular, Pd has been widely used in many works because of its fully reversible hydride formation properties under ambient conditions. When Pd is exposed to hydrogen gas, hydrogen...
molecules dissociate into atoms, which enter the interstitial sites of Pd. This induces mass and volume changes in the Pd host, as well as the change in the conductivity and dielectric properties. The volume change due to the hydrogen-induced lattice expansion in Pd is the basis of mechanical type hydrogen sensors. The change of conductivity and optical properties stems from the fact that electrons of the hydrogen atoms enter the s- and d-bands of Pd, leading to modification in the density of electronic states at the Fermi level and causing shifts of the energy bands. This, in turn, alters the conductivity and dielectric properties of Pd. While the change of Pd’s conductivity has been used in electronic hydrogen sensors, the modification in the dielectric properties promises its applications in optical hydrogen sensors.

Compared to electrical hydrogen sensors, which usually suffer from possible electric sparks, optical hydrogen sensors offer advantages of remote and contact-free readout and avoid spark generation. The change of refractive index alters the spectral feature of localized surface plasmon resonance (LSPR), including the broadening, shifting, and reducing the intensity of the LSPR peaks. However, the hydrogen-induced plasmon shifts and intensity changes are relatively small when the hydrogen volume concentration is below 4%. To enhance the sensitivity of plasmonic hydrogen nanosensors, various strategies have been applied, including using optical nanoantennas, core-shell structure, alloy particles, and composite materials. Unfortunately, the sensitivity of these optical hydrogen sensors is still limited by the broad bandwidth of the LSPR peaks. This makes the detection of peak shift difficult, and thus a high-resolution spectrometer is required for hydrogen sensing. Using Fano-like resonance of specially engineered nanostructures with a steep spectral edge can be an alternative to increase the spectral sensitivity of plasmonic hydrogen sensors. Shifts of the corresponding resonances result in significant intensity modulation at a fixed frequency due to the steep spectral edge.

For most optical sensors, a broadband illumination source and a spectrometer are mandatory to perform spectroscopic analysis. However, for practical applications, a single-color intensity distribution that can be read out without a spectrometer is more attractive. In this work, a 2D metal–insulator–metal plasmonic Doppler grating (MIM-PDG) has been specially designed for hydrogen sensing based on Fano resonance. The MIM-PDG consists of a Pd layer on top of an insulating Al₂O₃ layer deposited on a single-crystalline Au flake. Upon the absorption of hydrogen gas (0–4%), the Pd layer changes its phase to Pd-H, leading to a significant change in the refractive index and volume, further modifying the azimuthal angle-dependent transmission intensity. By plotting the calibration curve of the relative change (Q₁) at a specific azimuthal angle as a function of hydrogen concentration, the H₂ uptake can be quantitatively evaluated. Due to the interference of the MIM magnetic mode inside the Pd-Al₂O₃-Au cavity and the propagating surface plasmon polariton (SPP) mode on the Al₂O₃/Au interface, the MIM-PDG platform exhibits clear Fano-like resonance in the transmission spectrum. Since the Fano resonance varies with the grating periodicity, at a fixed wavelength, the chirped grating of MIM-PDG manifests the Fano resonance as a spatial (angular) distribution of transmission intensity with a Fano-like profile. We carefully analyze this kind of single-color “spatial” Fano profile and developed an analytical model to fit the experimental data. The change in transmission profile due to H₂ uptake was also analyzed. Such intensity and image-based hydrogen sensing are quantitative and spectrometer-free. It only requires a simple imaging system and image analysis software. It is thus a suitable method for sensing in microfluidic channels or for cellphone-based optical gas sensing.

2. Result and Discussion

2.1. Design and Fabrication of the PDG

The Plasmonic Doppler Grating (PDG) structure was designed to provide continuous and broadband lattice momentum for photon-to-plasmon coupling. The grating periodicity is chirped in the azimuthal direction, as demonstrated in our previous works. The trajectory of the PDG mimics the wave fronts of a moving point source of waves that exhibits Doppler Effect. Therefore, the trajectory of the nth ring can be described by the radius increment (Δr, similar to the source wavelength) and the ring center shift (d, similar to the source velocity) as

\[(x - nd)^2 + y^2 = (nΔr)^2\]  

(Figure 1a shows the schematic of a MIM-PDG with a chirped periodicity varying continuously from \(Δr + d\) to \(Δr - d\) which corresponds to an azimuthal angle from \(φ = 0°\) to \(180°\). The relationship between the periodicity of the grating (P) and azimuthal angle (φ) is given by

\[P(φ) = ± d \cos φ + \sqrt{(d^2 \cos 2φ + 2Δr^2 - d^2)/2}\]  

With the knowledge of incidence angle (θ), resonance order (m), and the material properties (\(ε_m\); metal permittivity; \(n_d\); effective index of the dielectric environment) the momentum matching condition for photons and plasmons via a metallic grating can be described as,

\[
\frac{2\pi}{λ_0} n_d \sin θ + \frac{2mπ}{P} = \frac{2\pi}{λ_0} \sqrt{\frac{ε_m - n_d^2}{ε_m + n_d^2}}
\]  

(3)

Inserting Equation (2) into Equation (3), we obtain an equation describing the vacuum wavelength (λ₀) and the light-plasmon coupling azimuthal angle (θ),

\[
λ_0 = \frac{±d \cos φ + \sqrt{(d^2 \cos 2φ + 2Δr^2 - d^2)}/2}{m} \left(\frac{ε_m - n_d^2}{ε_m + n_d^2} - n_d \sin θ\right)
\]  

(4)

For a specific PDG operating at a fixed wavelength, the photon-to-plasmon coupling angle φ changes with the refractive index

For a specific PDG operating at a fixed wavelength, the photon-to-plasmon coupling angle φ changes with the refractive index n_d, showing the index sensing capability of PDGs. Fano resonance is introduced in the design to enhance the sensitivity. A Pd-Al₂O₃-Au MIM structure is fabricated on top of chemically synthesized gold flakes (thickness = 120 nm).
The reason for using MIM geometry is that they support dark magnetic modes,[22] which couple with the SPP resonance and lead to Fano resonance. In the experiment, a microscope coverslip coated with a 40-nm indium tin oxide (ITO) layer was used as a conductive transparent substrate to avoid charging effect during focused ion-beam milling (FIB) and scanning electron microscope (SEM) imaging. The gold flakes were first transferred onto the ITO-coated coverslip. The Al2O3 layer (thickness = 100 nm) was then prepared on the surface of the flake by electron beam evaporation. On top of the Al2O3 layer, a 20-nm thick Pd layer was coated by electron beam evaporation. The PDG structure was then patterned on the MIM layered structure by FIB milling. Two sets of design parameters, Δr and d, have been chosen to fabricate the MIM-PDGs. The SEM images of the fabricated PDGs are shown in Figures 1b,c. For each MIM-PDG, only one circular ring was completely milled through by FIB until the ITO layer. Rest of the circular rings were slightly milled (depth = 20 nm) to create gratings only in the Pd layer. Overall, the MIM-PDG contains more than ten circular grooves and only one circular slit for light to transmit to the side of SiO2 substrate. The thickness of Al2O3 layer was chosen based on the results of FDTD simulations, where the transmission through the completely-cut slit shows the maximum at 633 nm when the thickness of Al2O3 is 100 nm (Figure S1, Supporting Information). Due to the high resistance of the Al2O3 layer to FIB, a funnel-like slit with a wide-open gap (about 180 nm) at the top of the slit and a narrow valley (about 27 nm) at the bottom (inset in Figure 1c) was created. In the simulations, this funnel-like geometry was approximated by an effective vertical gap. Compared to the reflection-type PDG, transmission-type PDG is advantageous for its low background and high signal-to-noise ratio because only the photons that couple into surface plasmons via the grating can transmit through the subwavelength slit and be detected on the side of SiO2 substrate.

2.2. Optical Response of the MIM-PDG

To obtain the spectra of the transmitted light at different azimuthal angles, we used a home-built spectral mapping system (Figure 2a). Briefly, unpolarized white-light (550–790 nm) in the Köhler illumination scheme was blocked by a ring aperture to create ring illumination via a condenser (Air, N.A. = 0.3, Zeiss) at an incident angle of 17.45°. Light transmitting through the slit was collected by an oil objective (Plan-Apochromat 63× oil Iris, N.A. = 0.7–1.42, Zeiss) and focused into the entrance slit of a spectrometer (SR-303i-A, Andor) by an achromatic lens (AC254-300-A-ML f = 300 mm, Thorlabs). The MIM-PDG sample was placed on a piezo stage (P-517.3CD, Physik Instrument) and scanned across the detection area defined by an effective pinhole in the detection beam path (Figure S2, Supporting Information). Figure 2b shows the image of the full-spectrum intensity obtained from the spectral mapping on the PDG shown in Figure 1b. To analyze the azimuthal angle-dependent transmission spectrum, thirteen transmission spectra were recorded along the azimuthal angle from φ = 0° to φ = 180° with an angle step of 15°. The red squares in Figure 2b mark the observation areas of 3 × 3 pixels, from which the angle-dependent spectra were extracted. By selecting the output wavelength, transmission image at any chosen wavelength can be reconstructed. Figure 2c shows four transmission intensity images recorded at 550, 600, 650, and 700 nm. As can be seen, the intensity maxima appear at different azimuthal angles depending on the wavelength. This demonstrates the color-sorting capability of the MIM-PDG.[46] Figure 2d shows the thirteen normalized azimuthal angle-dependent spectra obtained from the experiment and FDTD simulations. The experimental spectra are well-reproduced in the simulations. The transmission spectra obtained at angles between 90° and 120° all exhibit clear Fano-like spectral line shape due to the interference of the MIM magnetic resonance with the grating-coupled delocalized SPP on Al2O3/Au interface.[50] The electromagnetic field distributions have been simulated to confirm the origin of the Fano resonance of our MIM-PDG structure (Figure S3, Supporting Information). Since the Pd grating is involved in the MIM mode, the hydrogen absorption by the Pd is expected to alter the spectral Fano-line shape of each grating and thus the spatial Fano profile of the MIM-PDG. As we will show later, this spatial Fano profile allows us to quantify hydrogen concentration.
Figure 2. a) Optical setup for spectral mapping on the MIM-PDG. The red arrows on the sample illustrate the propagating surface plasmons. Unpolarized ring-shaped white light illumination at $\alpha = 17.45^\circ$ (N.A. = 0.3) is created by a ring aperture placed at the back focal plane of the air condenser. b) Total transmission intensity from the circular slit of the MIM-PDG. The blue lines mark the horizontal and vertical axes of the MIM-PDG. The red squares mark the areas (3 x 3 pixels in the image), from which the angle-dependent spectra (angle step = 15°) are extracted. (Scale bar: 1 µm). c) Single-wavelength transmission intensity images at four selected wavelengths, namely 550 nm (upper left), 600 nm (upper right), 650 nm (lower left), and 700 nm (lower right). (Scale bar: 1 µm). d) Normalized transmission spectra at different azimuthal angles obtained from the experiment (upper panel) and FDTD simulations (lower panel).

by analyzing the azimuthal angle-dependent intensity on MIM-PDG at a single wavelength.

### 2.3. Spectrometer-Free Hydrogen Sensing Based on Fano Resonance

#### 2.3.1 Characterization of the Optical Response at a Single Wavelength

To perform spectrometer-free hydrogen sensing, we monitored the effect of hydrogen uptake on the angle distribution of the transmission intensity at 633 nm. A similar MIM-PDG with the best-optimized design parameters ($d = 80$ nm and $\Delta r = 340$ nm) was fabricated (Figure 1c). The optimized MIM-PDG shows a transmission maximum around $\phi = 70^\circ$ at 633 nm. The hydrogen gas concentration was controlled by a home-built gas mixing system as described in our previous work. Briefly, the concentration of the hydrogen gas was controlled between 0% and 4% by tuning the ratio of the flow rate of nitrogen and hydrogen gases. The sample is placed in a home-built sample holder with a gas chamber, which allows the injection and outlet of various hydrogen-nitrogen mixtures at a constant total pressure. The overall flow rate of the nitrogen and hydrogen mixture is controlled to be 100 sccm at a total pressure of 1 atm. The MIM-PDG sensor was placed in the gas chamber and the experiment was performed by illumination and detection through the transparent windows above and below the sample, respectively. The details of the gas mixing system and the sample holder can be found in our previous work.

Single-color illumination source was created by filtering the white light source with a laser line filter centered at 633 nm (bandwidth = 3 nm, FL632.8-3, Thorlabs). This allows us to perform hydrogen sensing by directly observing the change in the angle distribution of the transmission intensity without using a spectrometer. Different from spectral mapping described in the previous section, here, the transmitted light at 633 nm from the circular slit was directly imaged by a CCD camera (iXon, Andor, UK) with 10-s exposure time. Figure 3a shows the CCD image acquired under pure nitrogen atmosphere (0% hydrogen). To obtain the transmission intensity angle profiles at different hydrogen concentrations in Figure 3b, we use a filter to select the slit area with a single-pixel width, each pixel corresponds to one intensity value and the pixel coordinate on the slit can be transformed into an azimuthal angle (Figure S4, Supporting Information). Upon the absorption of hydrogen gas, changes in the transmission intensity were observed at several specific azimuthal angles. To clearly visualize the effect on the transmission and remove the influence of source fluctuation, we plotted the relative change, $Q = (X_i - X_0)/X_0$, as a function of azimuthal angle in Figure 3c. Here, $X_0$ and $X_i$ are the angle-dependent transmission intensities measured in pure nitrogen gas (0% hydrogen) and in a mixture gas with 1% to 4% hydrogen concentrations, respectively. Three features are observed in Figure 3c. First, at specific angles (e.g., $\phi = 155^\circ$), the deviation of the relative change from the zero line, either positive or negative, is proportional to the hydrogen concentration. This is due to the influence of the hydrogen uptake on the resonance of the Pd gratings. This allows us to easily establish a calibration line by plotting the $Q$ at the most sensitive period versus the hydrogen concentration. Figure 3d shows an exemplary calibration curve using the $Q$ from the grating period at $\phi = 155^\circ \pm 5^\circ$, which is the most sensitive grating to hydrogen absorption. Second, the angle profile of the transmission intensity does not show angle shift upon absorption of hydrogen. This is because hydrogen uptake only slightly changes the coupling between the two modes involved in the Fano resonance. Therefore, the modification in the undulation of the Fano spectrum is more pronounced than that in the spectral shift. Consequently, the profile of the transmission angle distribution remains almost constant.
the same but the intensity undulation exhibits clearly observable changes. Third, the change in the transmission intensity is not uniform but angle-dependent. Increasing hydrogen concentration can lead to an increase, decrease, or no change in the transmission intensity, depending on the azimuthal angle. For example, the transmission at $\phi = 0^\circ$ and $\phi = \pm 155^\circ$ increases with increasing hydrogen concentration, whereas the transmission at $\phi = \pm 75^\circ$ decreases with increasing hydrogen concentration. The transmission intensity of the grating around $\phi = \pm 90^\circ$ is not responding to the absorption of hydrogen. The reason for the different responses to hydrogen absorption is as follows. First, the Fano-like transmission spectrum shifts with azimuthal angles (Figure S5, Supporting Information). Therefore, for gratings at different azimuthal angles, the selected wavelength for hydrogen sensing is located at different relative spectral positions of the Fano line shape. Since the absorption of hydrogen gas only slightly changes the coupling of the two modes involved in the Fano resonance, the modification in the undulation of the Fano spectrum is much more pronounced than the spectral shift. As a result, the chosen wavelength of 633 nm can sit on the relative spectral positions that are sensitive or insensitive to the absorption of hydrogen. In other words, the variation of the spatial transmission profile depends on where the selected observation wavelength is located relative to the Fano spectrum at the specific azimuthal angle. For example, at $\phi = \pm 75^\circ$, the selected observation wavelength of 633 nm sits at the peak of the Fano spectrum, which decreases with the absorption of hydrogen. Differently, at $\phi = \pm 155^\circ$, the Fano feature is out of the observation spectral window and the selected wavelength of 633 nm is just located on a spectral position of continuum background, of which the transmission increases with hydrogen absorption. As for the gratings around $\phi = \pm 90^\circ$, the selected wavelength of 633 nm hits exactly the iso-point of the Fano spectrum, at which the transmission intensity is completely insensitive to the hydrogen absorption. Such angle-dependent optical response of MIM-PDG, in fact, provides very useful information for the users to select the correct grating periodicity for different targeted applications. According to Figure 3c, gratings around $\phi = 155^\circ$ exhibit the largest response to hydrogen absorption and are most suitable for hydrogen sensing. If the application requires the grating to provide stable transmission insensitive to the fluctuation hydrogen concentration, the grating around $\phi = \pm 90^\circ$ should be used. Note that detection limit, a commonly used performance index for many analytical methods, is not useful here for two reasons. First, the MIM-PDG sensor is not designed to detect a very low concentration of hydrogen. Instead, it aims to monitor the hydrogen concentration around the explosion threshold (4%). Therefore, the most relevant feature is the optical response for hydrogen concentrations between 1% and
4%, not the detection limit. Second, different periods of the MIM-PDG respond to the change in hydrogen concentration differently. That means, depending on the azimuthal angle, the transmission intensity may be positively correlated, negatively correlated, or entirely insensitive to the hydrogen concentration. Therefore, a single detection limit is not a useful performance index for the MIM-PDG sensor presented in this work. As a reference, we estimate the detection limit of the grating at the azimuthal angle $\phi = 155^\circ \pm 5^\circ$. The estimated detection limit is about 0.24% of hydrogen concentration (Figure S6, Supporting Information). The reproducibility of the method is also provided in the Supporting Information. Within four test rounds, the periods at $\phi = 155^\circ \pm 5^\circ$ and $\phi = 75^\circ \pm 5^\circ$ show reproducible optical responses negatively and positively correlated to the increase of hydrogen concentration, respectively.

### 2.3.2 Modeling the Spatial Fano Profile

To understand the origin of the change in the angle-dependent transmission intensity, that is, the “spatial” Fano profile, we compare the FDTD simulations with the experimentally observed changes of the intensity distribution due to the absorption of hydrogen. We investigate the change by fitting the spatial transmission profile with a spatial Fano resonance model. In our experimental system, the incident light is partially polarized after passing through various optical components in the experimental setup. This makes the angular transmission profile asymmetric about $\phi = 0^\circ$. The elliptical polarization of the illumination can be precisely determined by examining the angular asymmetry in the transmission profile (Figure S7, Supporting Information). The parameters of the elliptical polarization were then used to correct the experimental data distortion in Figure 4a. For clarity, in the following, we only show the corrected experimental results for the cases of 0% and 4% hydrogen concentration, representing the cases of pure Pd and Pd-H, respectively (Figures 4a). Upon the absorption of hydrogen, the experimental transmission intensity decreases, and the peak width increases.

The spectral interference of the SPPs on the Al₂O₃/Au interface and the MIM mode inside the Pd-Al₂O₃-Au cavity gives rise to the spectral Fano resonance. Since MIM-PDG is an azimuthally chirped grating, the spectral Fano resonance of the grating at each angle can be mapped onto the “spatial” domain and the spatial (angular) profile of the transmission intensity at a fixed wavelength also exhibits Fano-like line shape. The origin of such a “spatial” Fano resonance profile along the azimuthal direction is related to the modulation of phase and amplitude relation between the MIM mode and the SPP mode. Specifically, the resonance frequency of SPP mode varies with the palladium grating periodicity along the azimuthal angle, as described by Equation 4. The resonance frequency of SPP mode excited for a given period of grating can be evaluated by the dispersion relation of surface plasmons on the Al₂O₃/Au interface (Figure S8, Supporting Information). The spatial Fano resonance profile along the azimuthal direction at a given frequency can be modeled by,

$$ T(\phi) = k \frac{(q + \varepsilon)^2 + b}{1 + \varepsilon^2} $$

(5)

Here, $q$ quantifies the asymmetry of the spatial Fano resonance, $b$ is the responsible for Lorentzian background associated to optical dissipation/damping, $k$ is proportionality constant and $\varepsilon$ is the reduced energy scale given as,

$$ \varepsilon = \omega - \omega_{sp} - \omega_d \Delta \Gamma $$

(6)

where $\omega$ ($2\pi c / \lambda_0$, $c$ is the speed of light in vacuum) is the frequency of incident light, $\omega_{sp}$ is the resonance frequency of the SPP mode, $\Gamma$ is the effective damping of the Fano line shape and $\Delta$ is the shift in resonant energy transfer frequency from the resonance frequency of the polariton mode. The intensity transmitted from the MIM-PDG under different hydrogen concentrations from 0% to 4% was fitted with Equation (5) to obtain the resonance parameters in Figure 4a. The $q$ and $\Gamma$ parameters obtained from the fitting of azimuthal angular transmission profile are shown in Figure 4b. The numbers of all the parameters can be found in Table S1, Supporting Information. The parameter $\Gamma$ shows a linear increase upon absorption of hydrogen, indicating an increase of the effective damping of the Fano line shape due to the phase transition from $\alpha$-phase

![Figure 4. a) Experimental angular transmission profiles recorded at 0% (black) and 4% (red) hydrogen concentrations and the corresponding curves from fitting the experimental data points with the spatial Fano model. b) The $q$ (black squares) and $\Gamma$ parameters (red squares) obtained from the experimental transmission angle profiles and the corresponding calibration lines using least-square linear fit.](image)
Pd to β-phase Pd-H. The effect of hydrogen absorption is also seen in the q parameter which decreases linearly with hydrogen concentration indicating a decrease in the asymmetry of the spatial Fano resonance. The fitting parameters of the spatial Fano resonance indicate that the absorption of hydrogen leads the system towards a heavily damped Lorentzian mode. Overall, the spatial Fano profile can be fully described by our analytical model and the effect of the phase transition from Pd to Pd-H due to hydrogen absorption is correctly revealed in the fitted parameters.

3. Conclusions

In this work, a spectrometer-free single-color optical hydrogen sensor based on the Fano resonance in the MIM-PDG structure is demonstrated. The absorption of hydrogen results in refractive index change and volume expansion of the Pd layer, leading to a significant change of the Fano-like transmission spectrum, which further changes the spatial (angular) distribution of the transmission intensity. The MIM-PDG platform has been successfully applied to hydrogen sensing in the range of 0–4% and offers good feasibility for remote hydrogen sensing without the need for a bulky spectrometer and broadband illumination source. The MIM-PDG also provides angle-dependent optical responses of a series of gratings for the users to select the gratings highly sensitive or completely insensitive to hydrogen absorption depending on the targeted applications. Given the small footprint and spectrometer-free sensing capability, the applications of the MIM-PDG platform in lab-on-a-chip systems or cellphone-based optical sensing are anticipated.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

Financial supports from the Thuringia State Government within its Pro Excellence initiative (APC2020), DFG (HU2626/3-1, HU2626/5-1, HU2626/6-1, SFB 1375), and the Ministry of Science and Technology of Taiwan (MOST-103-2113-M-007-004-MY3) are acknowledged.

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

J.-S.H. and F.-C.L. conceived the idea. F.-C.L. and Y.-J.C. performed the optical measurement and numerical simulations. A.K.S. and J.-S.H. developed the spatial Fano model. F.-C.L., Y.-J.C., and A.K.S. analyzed the data. All authors contributed to the preparation of the manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

Fano resonance, optical hydrogen sensing, plasmonic grating, plasmonic sensors

Received: April 29, 2021
Revised: August 10, 2021
Published online: September 12, 2021
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