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Proceedings of SPIE, 25th International Conference on Optical Fiber Sensors, 2017 / vol.10323, pp.103235X-1-103235X-4

Quasiperiodic Nanohole Array Plasmonic Sensors on Optical Fibers

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ABSTRACT

Surface plasmon resonance has found plenty of sensing applications on various platforms from label-free biosensing to surface-enhanced spectroscopies. Quasiperiodic nanohole arrays with patterns such as the Penrose tiling have been demonstrated with surface plasmon resonance enhanced optical transmission. Here we transfer quasiperiodic nanohole arrays onto optical fibers and measure their optical performance in refractive index sensing. These quasiperiodic arrays show multiple and narrow resonances related to their geometric features. These resonances are high sensitive to the dielectric changes on the probe surface due to our high quality fabrication. The sensitivity of quasiperiodic nanohole arrays is comparable to that of periodic nanohole arrays and reaches the theoretical sensitivity limit as predicted by our universal sensitivity analysis. This result verifies our sensitivity theory on propagating surface plasmon resonance in a wider range beyond periodic nanostructure arrays. Our study demonstrates the quasiperiodic nanohole array based optical fiber is a high-performance plasmonic sensor.

Keywords: Quasiperiodic nanohole array, surface plasmon resonance, template transfer, optical fiber sensor

1. INTRODUCTION

Surface plasmon resonance (SPR) enhanced transmission through nanohole arrays perforated in metallic films provides a well-established route for label-free biological sensing from various molecular detection to protein dynamics. Periodicity plays a critical role in forming the transmission resonances of the periodic arrays. Recently, the enhanced transmission was also observed in quasiperiodic nanohole arrays [1], which contain the long-range order but lack translational Bravais symmetry. The lack of periodicity results in distinctive scattering dynamics of resonances. These resonance modes can lead to efficient photon trapping and surface interaction, resulting in high refractive index sensitivity. In addition, quasiperiodic arrays exhibit an increased number of SPR modes compared to periodic structures. Such multiple modes promise the implementation of multiplexing for sensing in one single array.

Optical fiber is a portable and cost-effective optical platform, which provides an efficient way of light delivery and signal collection for plasmonic sensors. The plasmonic fiber probe is uniquely suited for remote, in vivo and in situ applications. Many techniques have been specially developed for direct fabrication of regular nanostructures on the tip of optical fibers [2], such as electron-beam lithography (EBL), focus ion beam milling and interference lithography. These methods either suffer from low yield or require special and complex apparatus. By contrast, transfer techniques avoid these shortcomings through fab through fabrication of nanostructures on a traditional planar substrate, and then transfer of the nanostructures to fiber tips. However, most of the transfer methods require production of a new pattern each time before transfer. This situation is especially time-consuming in the case of quasiperiodic structures, because none of parallel methods are capable of creating large-area general aperiodic arrays.

Here we report the integration of quasiperiodic nanohole arrays with optical fibers and their utilization as plasmonic sensors. The combination of template transfer [3] with EBL enables efficient fabrication of nonperiodic nanostructure arrays with high quality on optical fiber tips. The quasiperiodic structures show more SPR modes with the potential for multiplexing compared to periodic nanohole arrays. These characteristic modes are narrow and highly sensitive to

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25th International Conference on Optical Fiber Sensors, edited by Youngjoo Chung, Wei Jin, Byoungho Lee, John Canning, Kentaro Nakamura, Libo Yuan, Proc. of SPIE Vol. 10323, 103235X · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2263168

dielectric changes on the probe surface. The refractive index sensitivities of quasiperiodic nanohole arrays are measured to be as high as that of periodic arrays and approach the predicted theoretical limit. These qualities make the optical fiber sensor based on quasiperiodic nanohole array a promising candidate in plasmonic sensing.

2. EXPERIMENTAL AND RESULTS

2.1 Fabrication of the Quasiperiodic Nanohole Arrays

Two common quasiperiodic patterns are examined here: fivefold symmetric Penrose tiling [4] and twelvefold symmetric square-triangle tiling [5] with nanoholes at the vertices of the tiles. We choose EBL to produce our quasiperiodic nanohole arrays because it is capable of creating arbitrary two-dimensional patterns with high resolution. Rather than directly patterning structures on the fiber tip, we transfer the as-patterned quasiperiodic nanohole arrays from the template to the fiber tip with the template transfer technique. Many other transfer methods require fabrication of a new pattern each time before transfer. In contrast, we create a one-off nanohole array pattern on the template, which can be reused to replicate and transfer the same nanohole array onto the fiber tip. Specifically, the pattern of quasiperiodic nanohole arrays is first generated on a silicon wafer using EBL and deep reactive ion etching (DRIE) (Figure 1, Pattern generation). 100 nm thick gold film is then deposited onto the template, leading to the formation of corresponding holes during deposition. Next, the gold film with quasiperiodic nanohole arrays is transferred to the fiber tip using an epoxy as the adhesive layer, and the template can be reused after cleaning without damage (Figure 1, Template transfer). This transfer process can generate exactly the same pattern each time due to the reusability of the template. The combination of template transfer with EBL enables fabrication of arbitrary patterns and overcomes the drawback of other serial and time-consuming methods.

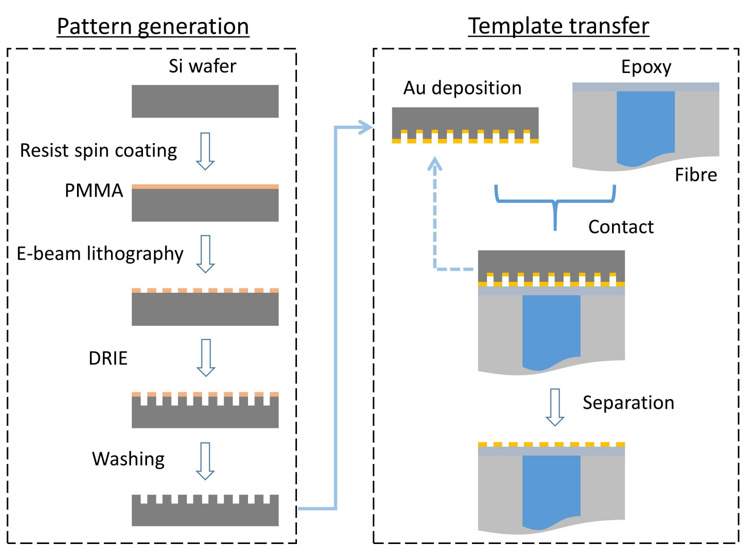

Figure 1. Fabrication of quasiperiodic nanohole arrays on the tip of optical fibers. The entire procedure is divided into two processes: pattern generation and template transfer of quasiperiodic nanohole arrays.

2.2 Characterization

Figure 2 shows the generated patterns on Si wafers. We designed the fivefold and twelvefold quasiperiodic nanohole arrays with the generalized dual multigrid method [6] and Stampfli inflation method [7], respectively. The tile edge length is 600 nm and the hole diameter is 200 nm in each pattern. The fivefold Penrose tiling consists of two kinds of rhombuses with equal edge length and acute angles of $\pi/5$/and $2\pi/5$, respectively. The twelvefold square-triangle tiling is only made of squares and equilateral triangles, in which the distances between nearest holes are the same.

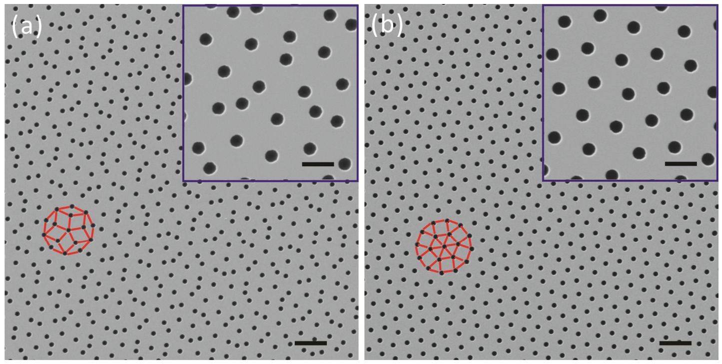

Figure 2. Nanohole quasiperiodic arrays on the templates. Scanning electron microscope (SEM) images of patterns for (a) fivefold Penrose tiling and (b) twelvefold square-triangle tiling. The images show the long-range order and rotation symmetry. Scale bars, 1 μm in (a) and (b), and 500 nm in the insets of (a) and (b).

2.3 Refractive index sensitivity

We use refractive index calibration solutions to determine the wavelength sensitivity, i.e., wavelength shift (nm) per refractive index unit (RIU), of our quasiperiodic nanohole arrays. Due to excitation of multiple SPR modes, distinct spectral features are observed between 700 and 900 nm in transmission (Figure 3). These peaks and troughs proportionally red shift as the refractive index increases due to the nature of SPR. The highest sensitivities of the lowest order SPR modes for the Penrose and square-triangle tilings are 605 and 554 nm/RIU, respectively. The overall performance of a SPR sensor is dominated by both the sensitivity of the resonance and its spectral line width. The full width at half-maximum (fwhm) of the narrowest resonance is down to 8.8 nm for the Penrose tiling and 5.3 nm for the square-triangle tiling. Such a narrow line width indicates the long lifetime of these SPR modes and high structure quality of our quasiperiodic nanohole arrays. Accordingly, the figure of merit (FOM), defined as the refractive index sensitivity divided by the corresponding fwhm, achieves 50 for the peak with 408 nm/RIU sensitivity.

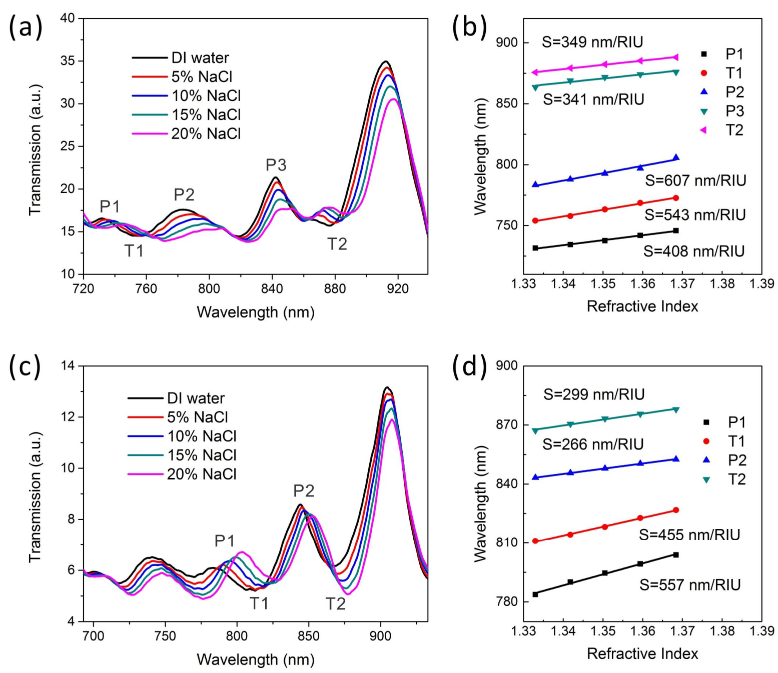

Figure 3. Transmission spectra for nanohole quasiperiodic arrays of (a) fivefold Penrose tiling and (c) twelvefold square-triangle tiling. Refractive index sensitivities obtained by linear fitting of (b) three peak (P1, P2, P3) shifts and two trough (T1, T2) shifts in (a), as well as (d) two peak (P1, P2) shifts and two trough (T1, T2) shifts in (c). The corresponding peaks and troughs are labeled in (a) and (c).

3. DISCUSSION

Our theoretical analysis reveals that the sensitivity is dominated by the SPR wavelength and the dielectric property of materials involved in the interaction, whereas metal nanostructures mainly act as a coupling media to generate SPR [8]. Accordingly, quasiperiodic nanohole arrays are supposed to have similar sensitivity at the same wavelength. To verify this prediction, the highest sensitivity of the lowest order SPR is plotted in Figure 4, along with theoretical values and a series of data for periodic nanohole arrays. Compared to periodic nanohole arrays, quasiperiodic arrays show equally high sensitivity, approaching the theoretical limit. This result in turn validates our universal sensitivity analysis for a wider range of plasmonic nanostructures.

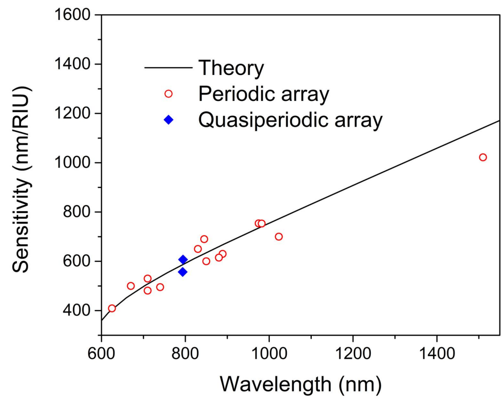

Figure 4. Sensitivity of quasiperiodic nanohole arrays compared to theoretical values and that of periodic arrays.

4. CONCLUSION

In summary, we show the potential of quasiperiodic nanohole arrays on optical fiber tips as plasmonic sensors. The combination of template transfer and EBL leads to an efficient procedure for high quality fabrication of arbitrary nanostructure arrays on optical fibers. The quasiperiodic arrays show as high sensitivity as periodic arrays, approaching the theoretical limit. High sensitivity combined with narrow line width and multiple modes makes quasiperiodic nanohole arrays a viable alternative to periodic arrays. In addition, their integration with optical fibers would facilitate their wide utilization in real world plasmonic sensing.

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