Angle Independent Fano Resonances in Bioinspired Nanostructured Fabry-Pérot Sensors

Daniel Assumpcao[1, 3], Radwanul Siddique[2,3], Vinayak Narasimhan[2], Hyuck Choo[2,3,4]

[1]Department of Electrical Engineering, California Institute of Technology, 1200 E. California Blvd., MC 136-93, Pasadena, California 91125, USA

[2]Department of Medical Engineering, California Institute of Technology, 1200 E. California Blvd., MC 136-93, Pasadena, California 91125, USA.

[3]Image Sensor Lab, Samsung Advanced Institute of Technology (SAIT), Samsung Semiconductor Inc., 2 N Lake Ave #240, Pasadena, CA, USA.

[4]Device Lab, Device & System Research Center, Samsung Advanced Institute of Technology (SAIT), Suwon, 16678, Republic of Korea.

.Author e-mail address: dassumpc@alumni.caltech.edu

Abstract: The utility of Fabry-Pérot based optical sensors is limited by their poor readout angle. We numerically demonstrate that adding bioinspired short-range-order nanostructuring to these devices leads to angle-independent Fano resonances, enabling wide angle optical sensing.

1. Introduction

Integrated optical sensors have the potential to empower a suite of novel functionalities with applications including monitoring for medical diagnosis [1], biosensing for disease study [2], and gas detection for environmental monitoring [3] to name a few. Despite their impressive performance in the laboratory, the translation of remotely readable sensors to practical settings has been limited by ease of readout. Outside the laboratory, the measurement of a sensor by an untrained user in an uncontrolled environment prevents optimal optical alignment. Therefore, it is vital these devices can be remotely readout even when misaligned.

Often the angle dependent optical behavior of sensors limits the maximum readout angle. This is particularly apparent in Fabry-Pérot (FP) resonance-based sensors, as a change in angle of incident light causes a shift in the resonance condition, leading to angle-dependent measurement errors.

Inspiration for the design of angle-independent optical devices can be drawn from nature, which has demonstrated a variety of exotic optical phenomena. In particular, the wings of the longtail glasswing butterfly (*Chorinea faunus*) display interesting and useful angle-independent optical properties due to the short-range ordered (SRO) distributed nanostructures found on the thin wing membrane [1].

In this work, we numerically analyze the angle independence enhancement to FP based optical sensors provided by adding glasswing butterfly inspired nanostructuring. We find that once the nanostructures are sufficiently large, new Fano lineshape resonances emerge due to the incoherent interference of the nanopillar and membrane modes. Furthermore, we show that this Fano resonance is significantly more tolerant to changes in the input angle due to the canceling out of the resonance shifts of the nanopillar and underlying membrane. This new understanding will allow the creation of novel angle-independent optical sensors.

2. Results

Nanostructuring consisting of nanopillars with variable heights was considered on a plain silicon nitride membrane (Fig 1). These nanopillars were distributed with SRO with a diameter of 300nm and average periodicity of 450nm, just like the nanostructures found on the glasswing butterfly. The underlying membrane demonstrates FP based resonance modes, thus emulating a general resonance-based sensor.

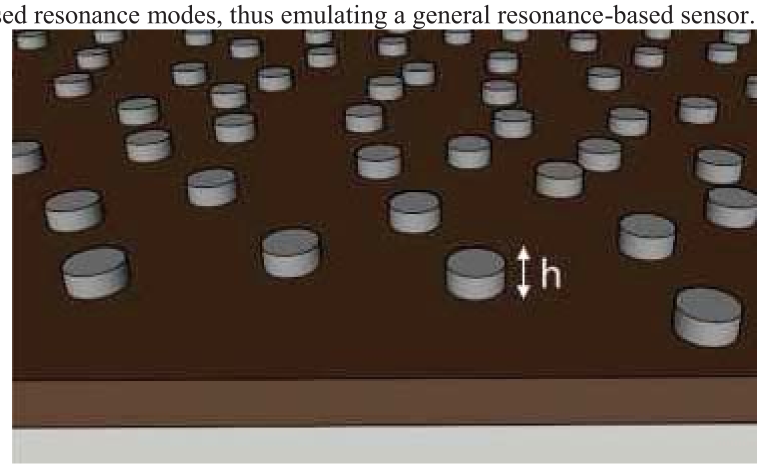

Fig 1. Diagram of nanostructured membrane, with nanopillars of height *h* on an underlying membrane and distributed with SRO

The transmission of this structure in the visible-NIR was simulated for variable nanopillar heights (Fig 2a). The unpatterned membrane shows Lorentzian shaped resonance peaks due to the FP resonances of the

10.1364/CLEOPR.2020.C2D_1

Authorized licensed use limited to: Samsung USA. Downloaded on April 18,2021 at 21:53:29 UTC from IEEE Xplore. Restrictions apply.

membrane. Once the nanopillars, of height h, are introduced, the shape of the spectrum is perturbed. At small heights, the lineshape of the spectrum is not significantly perturbed and only a redshift is observed due to the effective height of the membrane increasing (Fig 2a, h = 50nm), termed the light scattering regime. At large heights however, asymmetric Fano lineshapes begin to emerge (Fig 2a, h = 150nm, 200nm).

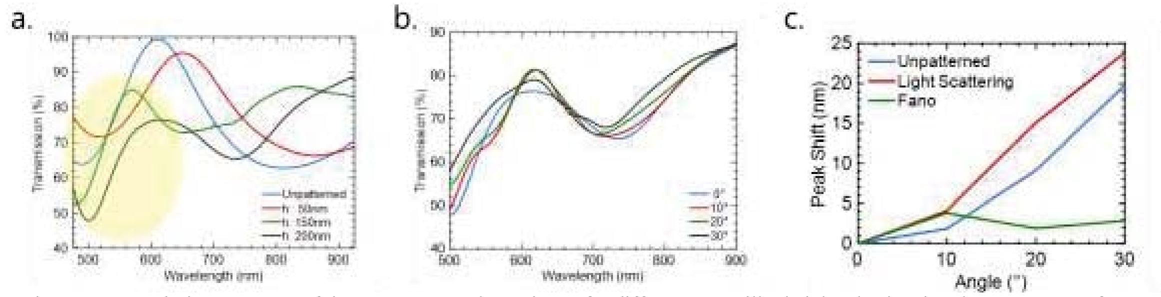

Fig 2. a. Transmission spectrum of the nanostructured membrane for different nanopillar heights, h, showing the emergence of a Fano resonance at large heights. b., the response of the Fano resonance to variable incident angles, showing an invariance in peak position. c. The peak shift of the nanostructured membrane for the different heights, showing the Fano resonances peak shift is significantly reduced.

The unpatterned membrane's resonances are highly sensitive to input angle due to their Fabry Perot nature, leading to a significant shift in the resonance versus input angle. The Fano resonance in the patterned membrane, however, shows almost no shift in its peak as the angle is varied (Fig 2b). To quantify this, the shift in the resonance versus the input angle was computed for the unpatterned membrane and patterned membrane in the "low scattering" and "Fano" regimes (Fig 2c). It is observed the low height nanostructuring does not significantly affect the angle independence performance. However, the Fano resonances in the Fano regime has a significantly reduced peak shift, an almost 10 fold reduction compare to the unpatterned membrane at an incident angle of 30°.

To understand the origin of this behaviour, the transmission of the SRO distributed nanopillars without the underlying membrane was simulated. As the height of the nanopillars increases, ripples emerge due to the modes of the nanopillars (Fig 3a). The joint membrane-nanopillar transmission was then computed using the transfer matrix method and assuming complete incoherence (Fig 3b). The emergence of Fano resonances is observed, thus demonstrating they are formed due to the incoherent combination of modes of the nanopillars and modes of the membrane. Finally the transmission of the nanopillars as the incidence angle is changed was simulated (Fig 3c). A red shift is seen, opposite of the blue shift of the membrane's FP modes. Thus intuitively, these two shifts cancel out in the Fano resonance leading to angle invariance.

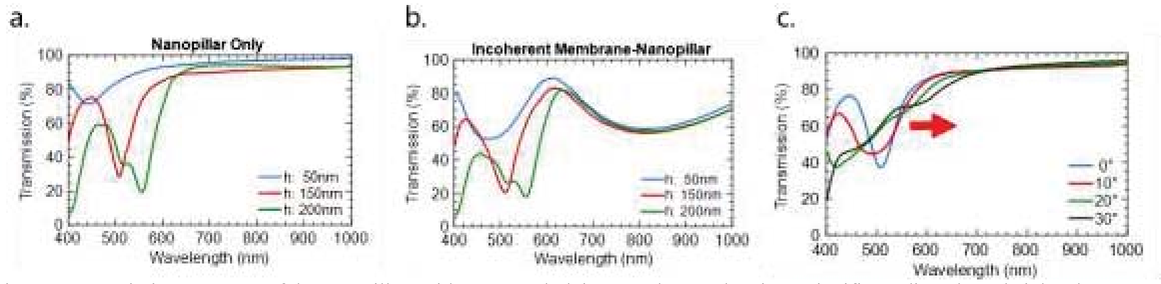

Fig 3 a. Transmission spectrum of the nanopillars without an underlying membrane, showing a significant dip at large heights due to modes of the nanopillar. b. The computed membrane-nanopillar spectrum assuming complete incoherence, demonstrating the origin of the Fano resonance. c. Transmission versus angle of the nanopillars, showing a red shift which cancels the blue shift of the membrane modes.

3. Conclusion

We numerically demonstrate that the addition of nanopillars distributed with SRO to a membrane leads to the formation of new Fano resonances due to the interference between the nanopillars and membrane. These Fano resonances show a significantly reduced change in peak location as the incidence angle is altered. By applying this same nanopatterning to Fabry-Perot resonance based sensors, these same wide angle Fano resonances can enable a new suite of wide angle optical sensors.

4. References

[1] V. Narasimhan *et al.*, "Multifunctional biophotonic nanostructures inspired by the longtail glasswing butterfly for medical devices," *Nat. Nanotechnol.*, vol. 13, no. 6, pp. 512–519, Jun. 2018, doi: 10.1038/s41565-018-0111-5.

[2] V. Narasimhan, R. H. Siddique, M. Hoffmann, S. Kumar, and H. Choo, "Enhanced broadband fluorescence detection of nucleic acids using multipolar gap-plasmons on biomimetic Au metasurfaces," *Nanoscale*, vol. 11, no. 29, pp. 13750–13757, Aug. 2019, doi: 10.1039/c9nr03178b.

[3] J. Liu, Y. Sun, and X. Fan, "Highly versatile fiber-based optical Fabry-Pérot gas sensor," *Opt. Express*, vol. 17, no. 4, p. 2731, Feb. 2009, doi: 10.1364/oe.17.002731.

Authorized licensed use limited to: Samsung USA. Downloaded on April 18,2021 at 21:53:29 UTC from IEEE Xplore. Restrictions apply.