Multilayer Plasmonic Structures for Ultra-Sensitive Refractive Index Sensing

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Abstract

Hyperbolic Metamaterials (HMMs) are multilayer structures which allow the propagation of Bulk Plasmon Polaritons (BPPs). BPP modes are result of interaction combination of Surface Plasmon Polaritons (SPPs) and Long-Range Surface Plasmon Polaritons (LRSPPs). These HMMs are made from nanolayers of alternating conducting and dielectric materials. They have many potential applications, including refractive index sensing, due to the very high effective refractive index (ERI) of modes propagating within these structures. We specifically are interested in biomedical refractive index sensing, and for this purpose our structures must achieve a very high sensitivity. A sensitivity on the order of 10^-7nm/RIU would be acceptable for some biomedical applications; however, a sensitivity of 10^-9nm/RIU would be optimal for the protein biosensing application we are pursuing. In order to achieve this goal, we are looking to optimize the grating structure or minimize confinement loss.

Introduction

Our goal is to optimize the HMMs for refractive index sensing. Preliminary research already confirms that HMMs with high effective refractive index have a very high sensitivity[1][2]. It was found earlier, that effective refractive index increases as we add more layers and/or decrease the thickness of the layers. Although an effective refractive index greater than 8.1 is possible to attain with the adjustment of these geometric parameters, manufacturing an HMM with those parameters could be too difficult. Therefore, our first goal was to prove that an HMM with an ERI double that of Germanium would be physically possible while keeping the geometric parameters fit for potential mass production. Our secondary goal was to calculate the sensitivity of the optimized structure.

ERI is given by:

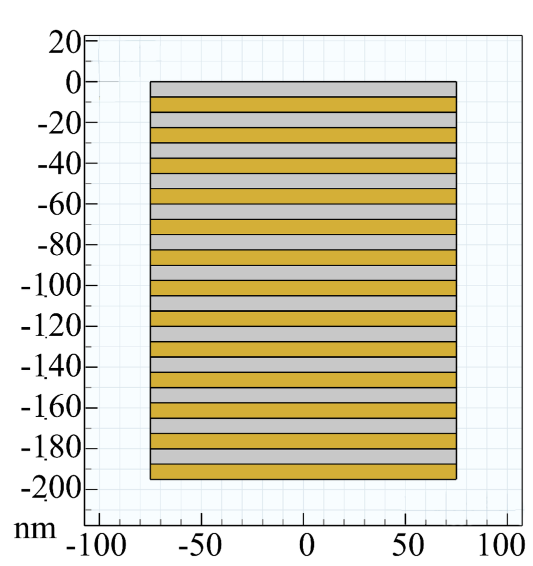
$$n_{\text{eff}} = \beta / k_0 = \beta \frac{\lambda_0}{2\pi}$$

The following Bragg Diffraction equation was used to determine the sensitivity of our structure.

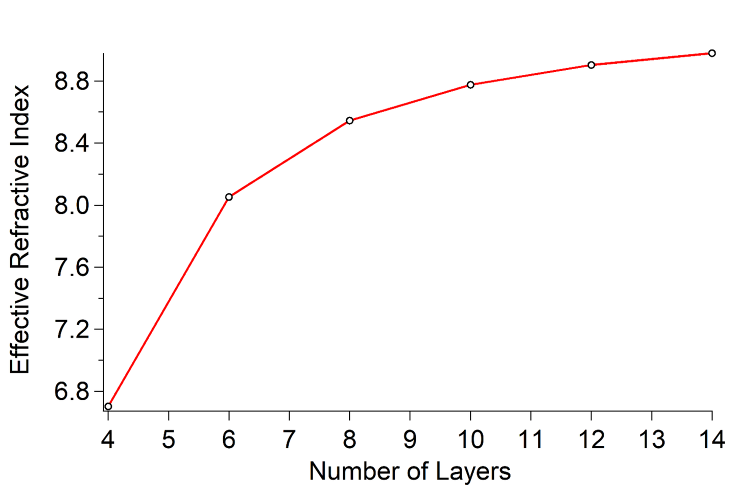
$$n_c \sin\theta = n_{\text{eff}} + m\frac{\lambda}{\Lambda}$$

We carried out Finite Element Method (FEM) simulations on COMSOL Multiphysics.

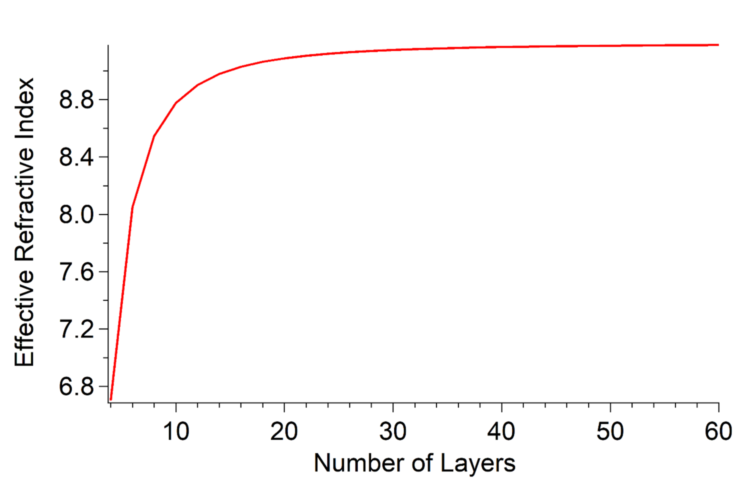
Geometric Optimization



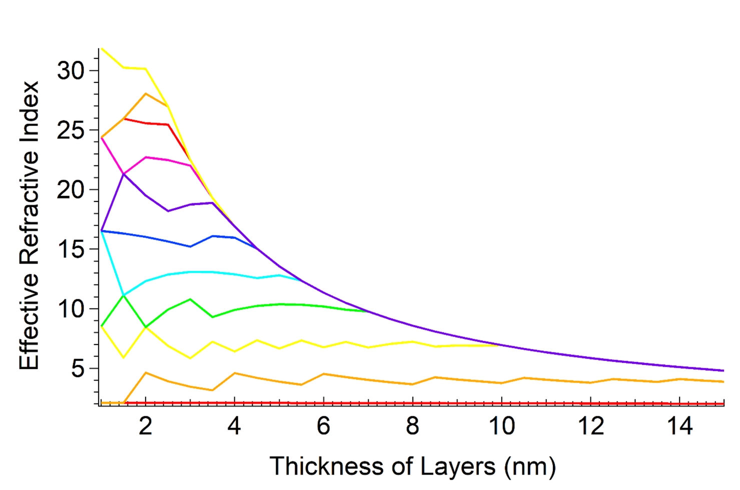
For the purpose of geometric optimization, we kept our structures rectangular, as seen on the left.



We held the thickness of the layers constant at 7.5nm and varied the number of layers, evaluating the ERI at each step. As number of layers increases, ERI also increases.

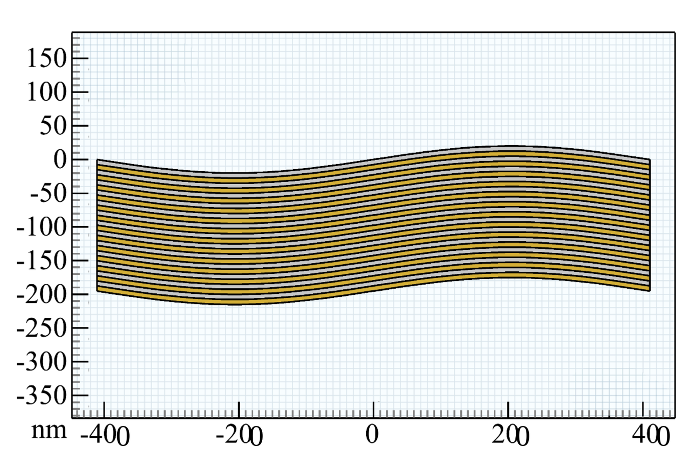


As we increase number of layers further, the effects it has on ERI stagnates beyond about 26 layers.

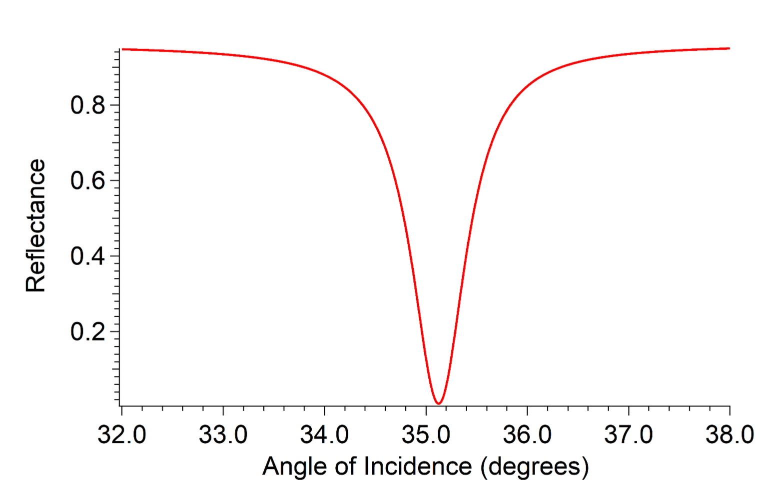


We then held the number of layers constant at 26 layers, varying the thickness from 1nm to 15nm. As seen in the graph to the left, thinner layers result in higher ERI.

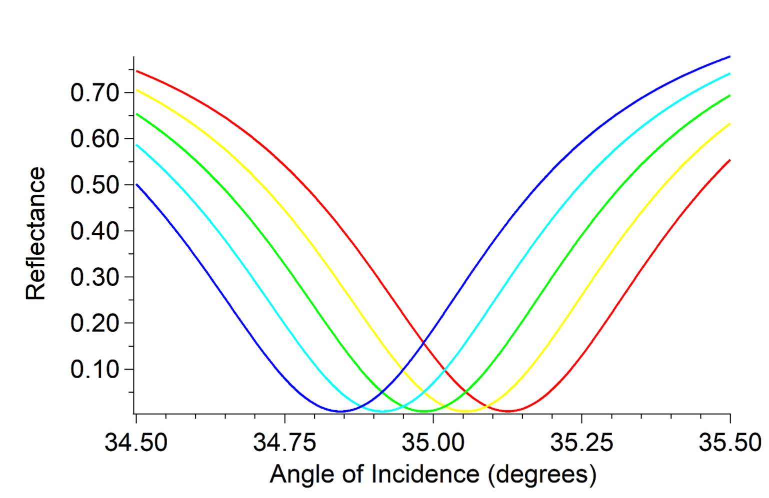
Determining Sensitivity



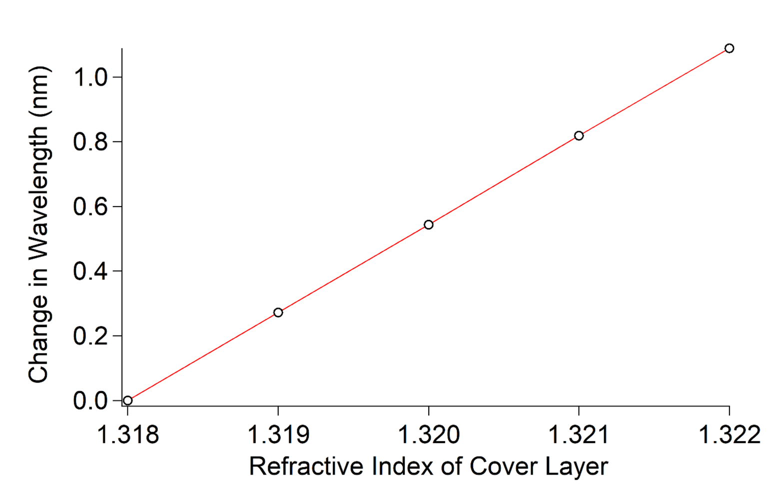
In order to couple the incident EM radiation with our structure, we used a grating. A grating period of 821nm and depth of 20nm was determined to be optimal.



We used the "C method" to calculate the reflectance as a function of incidence angle. The resonance angle can be seen in the graph on the left.



We then slightly varied the refractive index of the cover layer, resulting in a shift in the resonance angle.



Finally, we converted our data from angle shift to wavelength shift and determined the sensitivity to be ~272nm/RIU.

Analysis and Discussion

A plasmonic structure using alternating symmetric layers of gold and silicon dioxide can achieve twice the highest refractive index in nature with 26 layers of 7.5nm thickness. This structure's high effective refractive index is promising for sensing applications. The plasmonic structure with ~8.1 ERI achieves a sensitivity of ~272nm/RIU.

We have also begun using asymmetric layer thicknesses, which brings about promising results. We have been able to achieve a sensitivity of ~100nm/RIU using asymmetrical layers.

We were aware of the possible quantum mechanical effects that could take place with such thin layers; however, we used experimental data to reproduce the results we procured using bulk dielectric data and the outcome was the same. Therefore, we concluded that we could use the bulk dielectric data and consider the quantum effects negligible for now.

Our next steps will include optimization of the grating coupling. We believe the grating can be optimized further in order to increase the structure's sensitivity. We also will be examining other modes in an effort to increase sensitivity. Ultimately, we would like the structures to have a sensitivity on the order of 5nm/RIU for use in biomedical protein sensing.