

Optical sensing with high - index meta - structures

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Abstract

In this work, we have demonstrated the relevance of a high-index optical meta structure for sensing purposes.

Optical sensing with high-index meta-structures

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Abstract- Metamaterials, artificially designed man-made structures, have attracted a lot of attention since the last decade. In optics and photonics, metamaterials have led to the realization of structures with arbitrary refractive indices. One of the most important kinds of optical metamaterials are those which allow achieving large refractive indices. In contrast to ordinary optical materials having high refractive indices, high index meta-structures give one the chance to control the value of refractive index. In this article, it is shown that high index optical metamaterials are very useful for sensing applications. In fact, it is demonstrated that any small variation in the properties of a medium surrounding a high index optical metamaterial can cause strong shifts in the resonance frequency of the eigenmodes of the high-index structure. A comparison study between the sensitivity of the proposed optical and the existing ones is performed and the results are provided.

Key words—Sensing, Metamaterials, High-index structure, Optics.

I. INTRODUCTION

Sensing the variations in the environment or events is an important task. One of the best important platforms in which we can perform sensing is optics [1]. This is due of the fact that optical structures have often high confinement levels. Thus, changes in the properties of the surrounding medium yields significant changes in the spectra of the optical structures [2-4]. This helps us achieve extremely large values of sensitivity and figure of merit. Compared to conventional electronic sensors

[5], optical sensors have several important advantages. The first advantage is that they are more sensitive for the reason explained before. Another advantage is their very small size originating from the small wavelength of photons. The other advantages are the possibility of performing remote sensing by means of them, their very wide dynamic range, and their reliable operation.

In the past years, various optical structures have been proposed to do sensing [6-20]. One of the most important ways to do so, is the use of a medium possessing a high value of refractive index such as silicon. The fact that silicon has a refractive index larger than air means that the optical energy can naturally be confined in it. The spectral characteristics of this confined mode changes when some variation is applied in the ambient. Naturally, the more the mode is confined to the high-index medium, the better sensitivity of the environment. As a result, the sensitivity of the sensor can be tuned by changing the refractive index of the high index medium.

The use of natural optical materials having a high index of refraction results in several restrictions. The most important one is that it is not possible to have control over the sensor parameters such as its sensitivity, quality factor and figure of merit. In recent years, the idea of metamaterials [21-38] in the scientific community has allowed researchers to achieve optical properties that they would like to have. Metamaterials are structures designed to provide a desired characteristic, even though it is not available in nature. Metamaterials are constructed from a set of elements such as composite materials like metals. These composites are arranged in periodic or aperiodic patterns. The scale of arrangement is most of the time much smaller than the wavelength of operation. Consequently, metamaterials take their special properties not from the characteristics of their

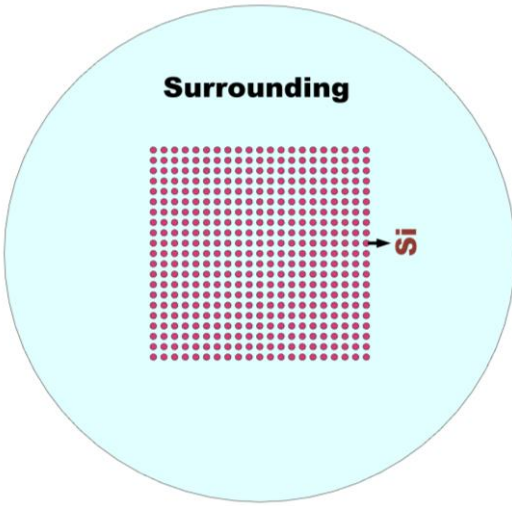


Fig. 1. The proposed high-index optical metamaterial doing sensing applications in optical range.

composites, but from their structure. Over the last two decades, metamaterials have allowed investigators to achieve phenomena which are not possible to achieve with ordinary materials found in nature. For instance, metamaterials have made realization of media with negative refractive index possible. This leads to various interesting effects, which are not possible to achieve with ordinary materials, such as negative refraction, negative Doppler effect, focusing beyond diffraction limit and cloaking [21]. It should be noted that metamaterials have also enabled having media with almost zero index of refraction. More interestingly, metamaterials have also allowed realization of structures with high index of refraction, having arbitrarily large values of index of refraction [39-43]. Compared to the ordinary high index optical materials found in nature, high index optical metamaterial are superior since their optical characteristics, specifically their refractive indices can be tuned by engineering the subwavelength inclusions of the metamaterial.

In this paper, the relation of high-index optical metamaterials for sensing applications is demonstrated. More specifically, design and demonstration of a high-index optical metamaterial is provided that senses its environment by means of a change occurring in its spectral features when the parameters of the environment vary. The parameters of the sensor such as its sensitivity, quality factor and figure of merit are calculated numerically and compared with the previous structures. Such sensors are highly appealing in various fields. For instance, in biology, they can help detecting molecules or atoms by just tracking the changes in the spectral features of the structure.

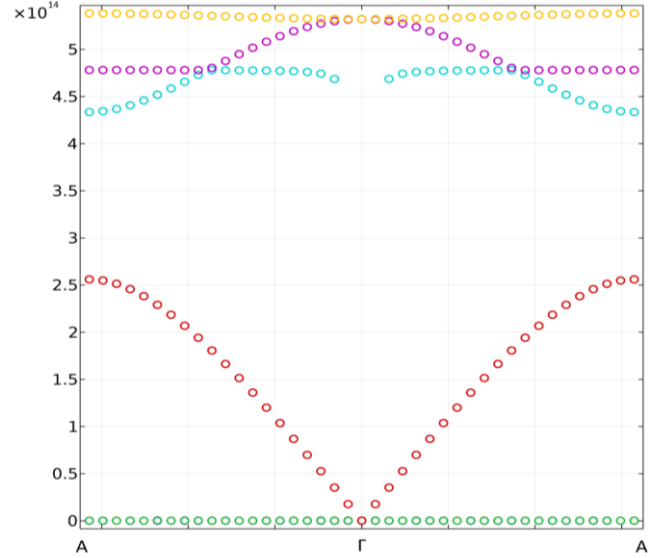


Fig. 2. Band structure of the proposed high-index structure.

The paper is organized as follows. In section II, the structure of the proposed high-index metamaterial is introduced. In section III, its performance is analyzed by providing the results of numerical simulations based on finite element method. Finally in section IV, the conclusion of the work is provided.

II. PROPOSED METAMATERIAL

The structure of the proposed metamaterial is depicted in Figure 1. It consists of silicon resonators arranged at sub wavelength. The silicon resonators have a refractive index of 3.2 and a radius of 10 nm. The metamaterial is surrounded by a lower index media that is air. The band structure of the metamaterial is obtained using Comsol Multiphysics 5.4, a full wave electromagnetic solver based on finite element method (Fig. 2). From the results of Figure 2 it is seen that the dispersion branch of the lowest order mode fall below the light cone. This implies that the metamaterial has an index of refraction more than air, showing its high index behavior. As a result, energy can be trapped inside the high index metamaterial.

In order to show this, the energy profile of the guided mode of the medium is calculated using FEM simulation. The whole structure was surrounded with perfectly matched layer boundary condition. The corresponding result are shown in Figure 3. It is obtained that the electromagnetic wave is confined to the metamaterial. This confinement can be exploited to sense the variations in the environmental parameters, as it is demonstrated in the next section.

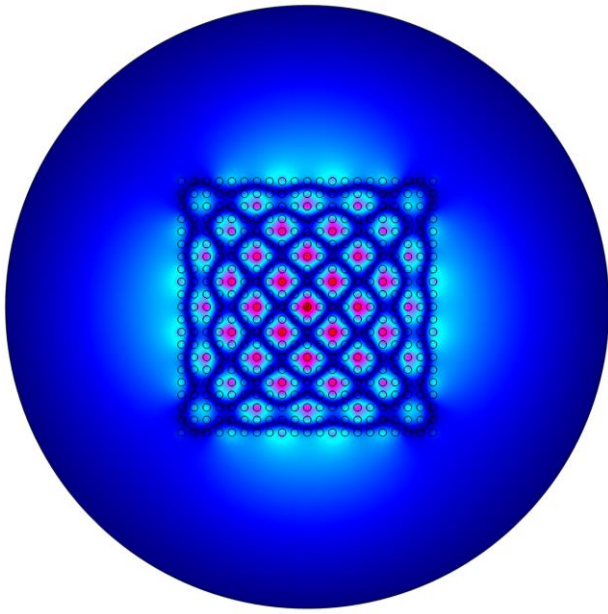


Fig. 3. Profile of the mode confined to the presented high-index structure.

III. NUMERICAL RESULTS

Now that a high index optical metamaterial is successfully demonstrated, it is aimed to be used for sensing the environment. In order to verify the possibility of sensing environment with the proposed high-index metamaterial, the eigen-modes of the structure are calculated using Comsol multiphysics, electromagnetic module. The structure has an eigenmode at the frequency of $f_0 = 216.28 \text{ THz}$. Then, it is supposed that the refractive index of the ambient is changed. Afterwards, the evolution of the frequency of the eigen-mode was investigated as a function of the refractive index of the ambient. The slope of this curve determines the sensitivity of the sensor, which is around 76 nm/RUI . This amount of sensitivity is better than many of the existing optical sensors proposed in the literature [44,45]. This is thanks to the strong confinement of the field inside the high-index metamaterial. It should be pointed that the sensitivity of the proposed sensor might in principle be enhanced by engineering the structuration of the metamaterial. To this end, one has to enhance the effective refractive index of the high index metamaterial. This could be obtained by changing the refractive indices of the inclusions of the metamaterial.

Another parameter which is important for a sensor is the linewidth of the resonance, defined as the ratio between the real and imaginary part of the obtained eigen mode divided by two. Based on finite element simulations, the quality factor of the sensor is also calculated and is obtained to be 20796. Based on the obtained sensitivity

and quality factor, the figure of merit of the sensor can then be obtained as $\text{FOM}=59.7$.

IV. CONCLUSION

In conclusion, in this paper, it was shown that high index optical metamaterials are very beneficial for sensing applications. This was demonstrated by designing an optical high index medium consisting of silicon dielectric arranged at subwavelength. It was shown that any small variation in the properties of a medium surrounding a high index optical metamaterial can cause large shifts in the resonance frequency of the eigenmodes of the high-index structure. By calculating the figure of merit and quality factor of the sensor, we also showed that the proposed sensor has relatively large values of sensitivity, quality factor and figure of merit. Such sensors can have some potential application in biology. For instance, they can help to detect molecules or atoms by just tracking the changes in the spectral features of the structure. In addition, future studies should be performed to enhance the sensitivity and figure of merit of the proposed sensor. To this end, one should consider changing the refractive indices of the cylinders/and or the periodicity of the metamaterial and investigate the way they affect the important parameters of the sensor.

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