بهبود ساختارهای هیبرید فوتونیک-پلاسمونیک برای استفاده در سنسورها و رزوناتورها

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چکیده- نانوساختارهای پلاسمونی به خاطر توانایی زیادی که در متمرکز کردن نور و تقویت میدان‌های الکترومغناطیسی دارند، در حسگرها و طیف‌نگارها به طور وسیع مورد استفاده قرار می‌گیرند. این ساختارها، قابلیت بهبود عملکرد حسگرهای نوری را به خصوص در مواردی که تعداد مولکول‌های ماده تحت شناسایی بسیار کم است یا مقدار جذب انرژی آن‌ها پایین است دارا می‌باشند. در سال‌های اخیر، واکنش نانوساختارهای پلاسمونی نسبت به انرژی نورانی تابانده شده در حضور مولکول‌های ماده مورد شناسایی، به طور وسیع مورد مطالعه قرار گرفته است. در این مقاله، تأثیر شکل نانوساختارها را روی حساسیت آن‌ها به نور تابیده شده بررسی کرده‌ایم. به این منظور، اشکال مختلف نانوساختارها مورد بررسی قرار گرفته‌اند و عملکرد آن‌ها در زمینه حساسیت و ضریب کیفیت با یکدیگر مقایسه شده است.

کلید واژه- حساسیت، ساختارهای هیبرید فوتونیک-پلاسمونیک، نانورزوناتورها، نانوساختارهای پلاسمونی، نانوسنسورها

Optimization of Hybrid Plasmonic-Photonic structures for Sensing and Resonator Applications

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Abstract- Plasmonic nanostructures are very beneficial in sensing and spectroscopy applications due to their strong light localization and field enhancement. They are capable of improving the performance of optical sensors, especially in cases which analyte molecules are few and their original absorption is low. In recent years the interactions of plasmonic nanostructures with light in presence of analyte molecules are extensively studied. Here, we have studied the effect of nanoparticles shape on their sensitivity to incident light. Various nanoparticle shapes are studied and their performance in terms of sensitivity and quality factor are compared.

Keywords: Hybrid photonic-plasmonic structures, Nanoresonators, Nanosensors, Plasmonic nanostructures, Sensitivity

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1 Introduction

Plasmonic nanoparticles made in different shapes from various metals have attracted researchers' interests significantly. This might be because of their uniqueness in light localization and field enhancement that enables them to have ultra-small mode volumes and enhanced light matter interaction which is vitally desirable for sensing [1] and light generating [2] applications. These nanoparticles are commonly made from metals such as gold and silver in much many diverse shapes and combinations. They can eye-catchingly be either fabricated on a solid substrate or freely dispersed in a liquid, based on desired performance and can be excited by free space illumination [3]. The extinction cross section of nanoparticles is inherently small and there's a challenging problem how to efficiently control the excitation of an individual particle [4].

In this paper, we present numerical results which show the efficiency of hybrid plasmonic-photonic structures in excitation and improved characteristics. In this hybrid platform, each nanoparticle is excited in a controlled way by means of guided wave photonic structures and the combination of nanoparticles or the modification of their shapes help us gather more desirable properties. We preferred Si_3N_4 for photonic platform because of its transparency in a wide range of frequencies from visible to infrared and the provided large index contrast [5]. Besides, we found that because of its low loss nature, Si_3N_4 is used in ultra-high quality microresonators and waveguides [6]. Gold is the material used as plasmonic material for its large field enhancement quiddity and tunable resonance frequency in a wide range which have caused this material to bebeneficial in a variety of applications [7].

2 Theory

Our proposed hybrid photonic-plasmonic structure consists of a Si_3N_4 ridge waveguide with the cross section of (w×h) which supports the transverse electric (TE) mode throughout the resonance of the structure [5], integrated with a gold nanoparticle or an array of nanoparticles as illustrated in Figures 1 and 2. The substrate of the photonic platform is silicon-dioxide (SiO_2). The guided mode propagating through the photonic waveguide, excites the resonance mode of each nanoparticle.

We have used finite difference time domain (FDTD) method to analyze the structures' operation. The waveguide transmission and reflection spectrum of a gold nanoring integrated on a photonic waveguide is shown in Figures 3 and 4, respectively. The remaining structures show the same spectrum, as well. It's evident that the transmission and the reflection spectrums exhibit a drop and a peak respectively because of the maximized extinction cross of the nanoparticles at their resonance frequency. This phenomenon causes the guided wave to be coupled to the nanorod and reflected back stronger. The remainder of the input optical power is transmitted through the waveguide.

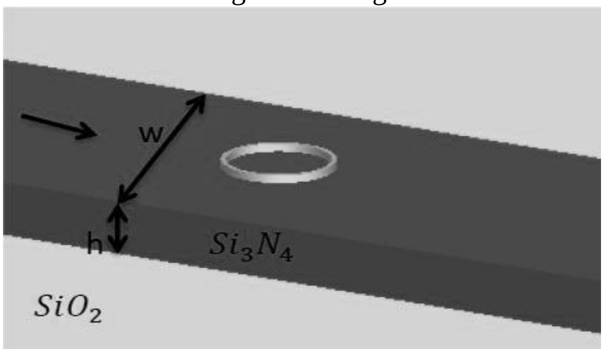


Figure 1: Integration of a gold nanoring on a (w×h) photonic waveguide

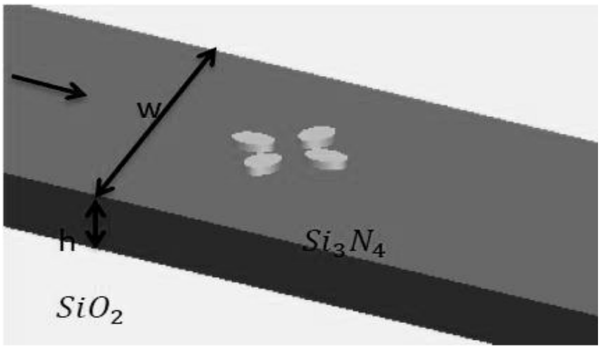


Figure 2: Integration of an array of nanorods on a (w×h) photonic waveguide

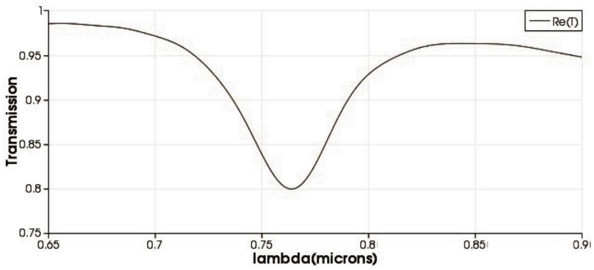


Figure 3: transmission spectrum of a gold nanoring integrated on a photonic waveguide

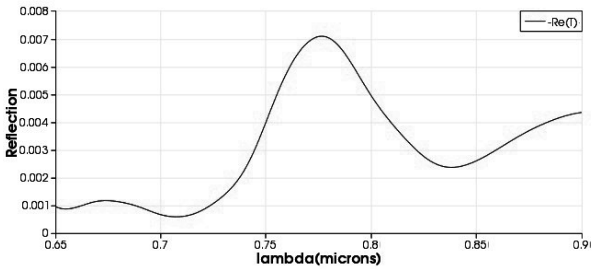


Figure 4: reflection spectrum of a gold nanoring integrated on a photonic waveguide

It's illustrated that as the SP mode order (l) increases, the effective volume decreases with $(l+1)^{-2}$ and the SP mode energy gets concentrated in a very small volume close to the surface of the nanoparticle. This phenomenon is very beneficial specially considering the fact that higher order modes aren't subjected to radiative damping, but the problem is that external fields cannot be coupled into any of the higher order modes [8]. The later obstacle encouraged us to design arrays of particles. In case of two particles of equal dimensions the dipole modes in both particles act as antennae allowing energy to be transferred in, this energy then is coupled into higher order modes of both particles through their coupling with the dipole mode of the other particle, allowing efficient coupling of the radiation into the gap region [8]. To design a well-organized array, we've examined arbitrary combinations of nanospheres and gaps between them.

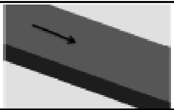
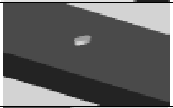
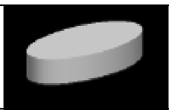
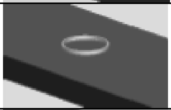
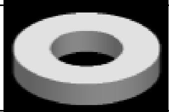
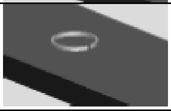
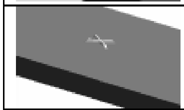
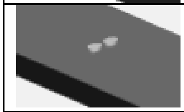
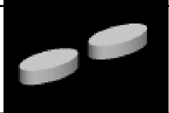
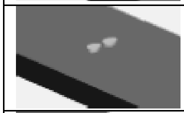
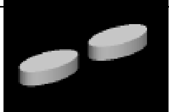
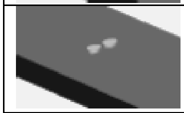
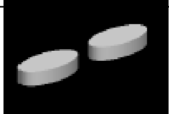
3 Discussion

In order to compare the operation efficiency of each composition and shape of nanoparticles, their vital properties are demonstrated in Table 1. It's crystal clear that an array of nanoparticles which is designed properly, has more desirable characteristics than a single nanoparticle overall. If the resonator application of the structure is of interest, the quality factor of the whole structure is considered as the determinant characteristic and if they are employed in sensors, their sensitivity which is defined as the ratio of wavelength variations to refractive index variations, is of more concern than other properties. It can be seen from Table 1 that we may decide which nanoparticle and set to choose for our particular purpose.

4 Conclusion

In a nutshell, we have demonstrated that integration of plasmonic and photonic structures can help us deploy the eminences of both in a hybrid structure and overcome one technology's defections by the other one's benefits. Using arrays of nanoparticles or refining their shapes provide us the possibility of improving the structures properties for our desired ones. Furthermore we mentioned that we must decide between different choices based on our application meaning that the best structure for sensing applications isn't necessarily the best to be used as a resonator. Considering the table provided in this paper, we conclude that an array of double nanorods can be the best choice as a resonator because of its high sensitivity (585). On the other hand, the highest quality factor (20) is associated to a single semiring which can be used as a good resonator. We must notice that this resonator has a very small mode volume and large field enhancement in comparison with the photonic resonators and integrating it with a photonic resonator enables us acquire higher quality factors than a plasmonic resonator [9]. Thus, by delicately integrating these structures with other integrated devices we can achieve a fully functional and highly efficient hybrid plasmonic-photonic circuit which fits our desires more than often.

Table 1:Comparison between quality factor and sensitivity of different sets of nanoparticles integrated on a (700nm×200nm) ridge waveguide. h and $\boldsymbol{d_i}$ are respectively thickness and diameter of the nanorods, x shows the distance of nanorods in arrays, and θ is the angle between cross arms and Ω is the equivalent angle of the omitted arc.

	*Nanostructure Geometry*	*Nano structure*	*Resonance wavelength (nm)*	*Structure Dimensions (nm)*	*Sensitivity (nm/RIU)*	*Quality factor*
		*Single nanorad*	*763*	$(d_1,d_2,h)=(50,28,30)$	*277*	*12*
		*Single nanoring*	*765*	$(r_{in},r_{out},h)=(100,110,29)$	*303*	*16*
		*Single semiring*	*767*	$(r_{in},r_{out},h,\Omega)=(100,110,30,10°)$	*308*	*20*
		*Single cross*	*873*	$(l,w,h,\theta_l,\theta_b)=(150,10,30,60°,60°)$	*515*	*15*
		*Array of double nanorods*	*700*	$(d_1,d_2,h,x_b)=(40,28,30,70)$	*333*	*11.5*
		*Array of double nanorods*	*652*	$(d_1,d_2,h,x_b)=(40,28,30,50)$	*578*	*12.7*
		*Array of double nanorods*	*662*	$(d_1,d_2,h,x)=(40,28,30,30)$	*585*	*12.5*
		*Array of four nanorods*	*670*	$(d_1,d_2,h,x_1,x_2)=(40,28,30,30,70)$	*486*	*12.5*

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