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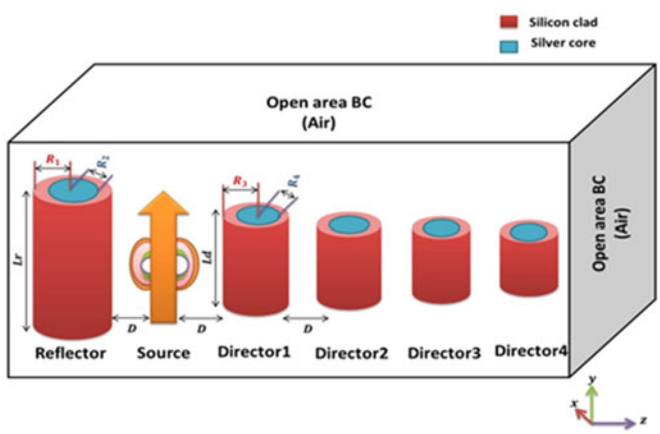

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Highly Directive Hybrid Yagi-Uda Nanoantenna for Radition Emission Enhancement

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Abstract: In this paper, a novel design of Yagi–Uda nanoantenna is introduced and numerically analyzed using finite integration technique via computer simulation technology software. The proposed nanoantenna consists of five core-shell nanowires with silicon cladding and silver core to achieve high directivity for wireless point to point applications. The proposed design shows a high directivity of 17.21 at a wavelength of 500 nm, which exceeds the spherical dielectric counterparts with directivity of 12. Therefore, an enhancement of 43.41% is achieved, which is mainly useful for spontaneous emission manipulation and photon detection. This enhancement is attributed to the silicon dielectric shell that exhibits magnetic mode with high refractive index, as well as the surface plasmon mode supported by the silver core. Additionally, the proposed cylindrical design has advantages in terms of high homogeneity of the field distribution, which overcomes the inhomogeneity field distribution of the nanosphere-based design.

Index Terms: Nanoantenna, directivity, surface plasmon, radiation pattern, finite integration technique.

1. Introduction

Recently, wireless communication has attracted a great attention in different applications such as satellites, cell phones, laptops, and other devices [1]. One of the most emergent devices in wireless communication is the optical nanoantenna [2]. The nanoantennas can control the light beam in a subwavelength scale [3]. The ability of the nanoantenna to transmit or transfer the propagating electromagnetic radiation into localized energy has gained intense research in many applications such as: sensing, photodetection, metasurfaces, medicine, photovoltaics, and energy-harvesting applications [4]–[7]. To improve the full potential of directional radiation, the optical Yagi-Uda was employed [8]. The idea was initiated from radio frequency (RF) technology, where Yagi–Uda antennas are used to realize high directivity [9]. The Yagi-Uda antenna has a simple design for fabrication with very narrowband response [2]. The standard Yagi-Uda antenna consists of a feed element connected with two types of passive elements: a resonant reflector and one or more directors [5]. The important parameter of the entire structure is the length of the feed element at which resonance occurs [8].

The lengths of directors and reflector are designed to direct the radiation in the forward direction with no radiation in the backward direction. Therefore, the length of the directors is shorter while the reflector length is longer than the feed element [10]. The first fabricated Yagi-Uda nanoantennas were made from metallic nanorods in analogous to the classical RF antenna design with directivity of 6.4 [11]. The arranged metallic nanorods can fulfill all the required RF antenna circumstances with high directionality due to the supported resonant plasmonic modes [5]. Recently, several works have been directed towards the far field region enhancement. In 2012, Liu *et al*. [3] enhanced the directivity up to 15.7 at wavelength of 603 nm by increasing the number of elements to eight elements (one reflector and seven directors) [3]. In the same year, a dielectric nanosphere antenna was designed with directivity of 12 at wavelength of 500 nm by Krasnok *et al*. [5].Two years later, Satitchantrakul *et al*. [12] proposed a four silicon nanosphere design with enhanced directivity of 12.52 at $\lambda = 660$ nm [12]. Further, an array of silicon nanorods has been introduced by Huang *et al*. [13] with enhanced directivity by compressing the radiation width to $\sim$3 nm in the x-direction [13]. Additionally Ma *et al*. [14] designed cubic silver Yagi–Uda nanoantenna with directivity of 17 at $\lambda = 633$ nm for collimated laser applications [14].

The plasmonic materials are commonly used in the field of nanophotonics due to the supported strong surface plasmon mode with high radiative decay rate [15]. However, the plasmonic materials have large dissipative losses which reduce the radiation efficiency [3], [5]. On the other hand, the dielectric nanoantennas have low dissipative losses, as well as high magnetic mode in the visible region [15]. However, a low radiative decay rate seems to be more prevailing [12]. The above mentioned characteristics of metallic and dielectric materials are responsible for inspiring the proposed design with high directivity, high efficiency, and high radiative decay rate.

In this paper, a novel design of directive nanoantenna has been introduced and analyzed. The proposed structure consists of five hybrid nanowires with silver core surrounded by silicon shell. The three design parameters of the nanowire structure; core radius, cladding radius, nanowire length; increase the design degrees of freedom and, hence, the nanoantenna directivity. The finite integration technique (FIT) method [16] has been used to numerically analyze the proposed structure. A directivity of 17.2 is obtained for the reported hybrid nanowire Yagi-Uda antenna with an enhancement of 43.41% at wavelength of 500 nm over the previously reported design by Krasnok *et al*. [5]. This enhancement is due to the magnetic and electric modes supported by the suggested design. The silver core (metal) has the ability to provide surface plasmon modes. Further, the silicon shell (dielectric) with high permittivity exhibits a strong magnetic field. In addition, the hybrid nanowire antenna shows a homogenous field intensity distribution compared with inhomogeneous field distribution produced by the spherical dielectric nanoantennas.

2. Design Considerations and Simulation Methodology

The investigated optical Yagi-Uda nanoantenna shown in Fig. 1 consists of five hybrid nanowires. Each element has a silicon cladding with silver core. In this study, the silver permittivity is taken from Johnson and Christy data [17]. The length of the driven element in the nanowire antenna (dipole source) is equal to L_f connected with a reflector of length $L_r = 1.25L_f$ to re-radiate the backward radiation to the specific direction [11]. Furthermore, four directors have been used of length $L_d = 0.9L_f$ with scaling factor S [11], [2]. The four directors have a silicon cladding of radius R_3 with a silver core of radius R_4. However, the cladding silicon and silver core of the reflector have radii of R_1 and R_2, respectively. Further, the distance D between the reflector and feed element is equal to the distance between two adjacent directors. The proposed design of the optical nanoantenna is simulated using electromagnetic 3-D finite integration technique (3-D FIT) [16] via computer simulation technology (CST MWS) software package [2]. To achieve high accuracy, the number of mesh cells per wavelength is taken as 15 cells per wavelength. Fig. 1 shows the 3-D computational domain for the simulated unit cell of the proposed Yagi-Uda design. The unit cell

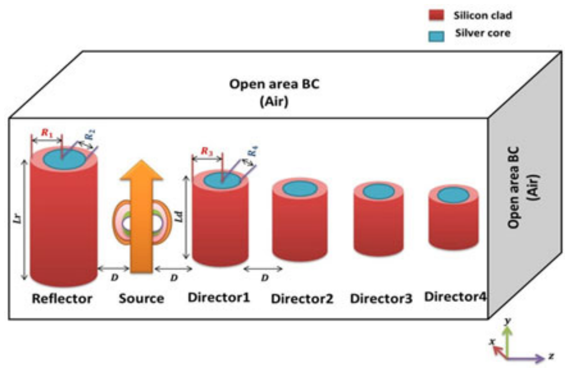

Fig. 1. Three-dimensional computational domain of the proposed hybrid nanowire Yagi-Uda nanoantenna.

is surrounded by air as an open area boundary conditions (BCs) along the x, y and z directions to give extra distances for the far field calculations. The length and the height of the unit cell are equal to 1500 nm and 400 nm, respectively. In this study, the optical nanoantenna is excited by the feed element that consists of discrete port connected between two perfect conductors nanoparticles with gap size of $g = 10$ nm. The directivity of the nanoantenna and the radiation efficiencies are used as a figure of merit to study the performance of the proposed nanoantenna. The directivity of the propagating radiation is defined as

$$D(\theta, \phi) = 4\pi \frac{P(\theta, \phi)}{\int P(\theta, \phi) d\Omega} \tag{1}$$

where $P\ (\theta,\ \varphi)$ is the radiated power per unit solid angle in the desired direction, divided by the power radiated per solid angle in all directions.

The radiation efficiency quantifies the electrical losses occur throughout the nanoantenna, and it is defined as

$$\eta = \frac{P_{rad}}{P_{rad} + P_{loss}} \tag{2}$$

where P_{rad} and P_{loss} are radiated and losses powers, respectively [5].

The fabrication of the proposed Ag/Si core/shell nanowire nanoantenna can be performed by employing the electron-beam (EB) evaporation technique [18]. The EB evaporation procedure uses an electron beam, controlled by a magnetic field, in order to melt a metallic source and hence a thin film can be created on the substrate [19]. This technique is operated at a very low vacuum level so that the mean free path of electrons is very high [20], [21]. Therefore, the produced thin film is uncontaminated by any foreign particles from the chamber [18]. The next step is to use electron beam lithography in order to define the nano-patterns. Then, the nanowires can finally be created by the etching process, followed by deposition of a-Si.

Another recommended fabrication method is the double beam laser ablation in liquid (LAL) [22]. The solid targets and solution environments can be designed using the LAL technique within a double-beam-induced method to fabricate nanostructures of noble metal-semiconductor compounds (core-shell nanostructures) [23]. The hybrid nanoparticle fabricated by the LAL method shows a strong electromagnetic response in the optical range and highly surface-enhanced Raman scattering (SERS) [22].

A third alternative is the conventional vapor–liquid technique for the synthesis of Ag/Si hybrid coaxial nanowire [24]. The Ag core nanowire development can be directed by the gold-catalyst-assisted vapor-liquid-solid process. However, the Si shell creation could be endorsed to the surface diffusion of the Si species through the liquid gold droplets to the nanowire surface [25].

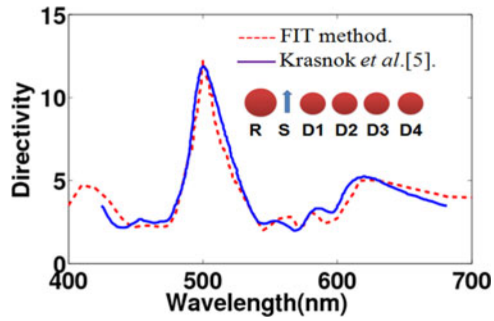

Fig. 2. Wavelength dependent directivities of silicon nanosphere calculated by the FIT and that reported by Krasnok *et al.* [5].

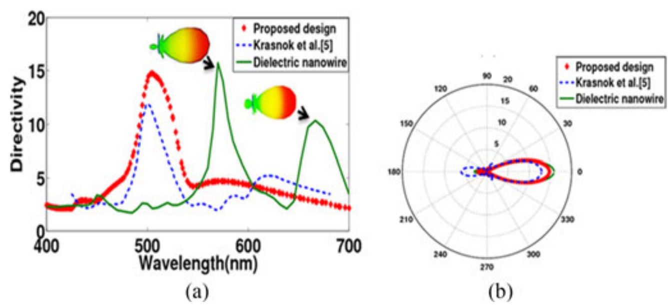

Fig. 3. (a) Wavelength dependent directivities of the proposed hybrid nanoantenna, cylindrical, and spherical dielectric nanoantennas [5] and (b) radiation patterns of the hybrid and spherical dielectric nanoantenna [5] at $\lambda = 500$ nm and radiation pattern of cylindrical dielectric design at $\lambda = 570$ nm.

Core/shell nanoparticles and several nanoantenna structures can be fabricated using the above techniques [18], [23], [24]. Therefore, it is believed that the proposed design can be fabricated successfully. Further, the reported design does not include curvature or sharp tips and the dipole source have a large gap size to facilitate the fabrication process [26].

3. Results and Discussion

To verify the simulation results calculated by the 3-D FIT method [16], the dielectric Yagi-Uda nanoantenna proposed by Krasnok *et al.* [5] has been initially considered. The dielectric Yagi nanoantenna consists of five silicon nanospheres, one reflector with radius $R = 75$ nm and four directors with radii $R = 70$ nm. The dipole source is placed in mid distance ($D = 70$ nm) between the reflector and the first director. The separation between two neighboring directors is also equal to D [5]. Fig. 2 shows the directivity versus the wavelength for the simulated design by Krasnok *et al.* [5] and that calculated by the 3-D FIT method. It may be noted from this figure that a good agreement has been obtained between the calculated results and that reported in [5].

In this study, the directivity enhancement and the power emitted in the Z-direction are also calculated by the FIT [16] via CST software packages. The proposed optical Yagi-Uda nanoantenna designs are illuminated by a dipole source that oscillates in the Y-direction. Fig. 3(a) shows a comparison between the directivity of dielectric spherical nanoantenna [5], the dielectric cylindrical nanoantenna and the proposed hybrid nanoantenna. The geometrical parameters of the proposed nanoantenna are listed in Table I. The length of the feed element is expected to satisfy the resonance condition [8]. In order to have a fair comparison between the reported design and the dielectric spherical nanoantenna [5], the same geometrical parameters listed in Table I has been used [5]. In this regard, the total radii of the directors and reflector and the distances between source-directors

TABLE I
Hybrid Nanoantenna Parameters

Radius (nm)	Reflector		Directors	
	R_1	R_2	R_3	R_4
	75	45	70	42
L_f		160 nm		
L_d		144 nm		
Scaling factor (S)		0.9		
L_r		200 nm		
D		70 nm		

and source-reflectors for the proposed design are selected similar to that reported by Krasnok *et al.* [5]. However, the lengths of the reflector and the director of the proposed design are chosen, as discussed in [2], [11]. It is evident from Fig. 3 that the proposed design increases the directivity up to 14.8 at $\lambda = 500$ nm, which exceeds that of the silicon nanospheres of 12 with an enhancement of 23.33%. However, directivity of 15.7 is achieved at wavelength of 570 nm for the dielectric nanoantenna. The optical resonance of the proposed design is shifted from $\lambda = 570$ nm (dielectric nanoantenna) to $\lambda = 500$ nm through controlling the shell thickness (silicon) as well as the core radius (silver). This satisfactorily agrees with the results obtained by Cheng *et al.* [27]. It is also worth noting that the dielectric nanoantenna radiates predominately at $\lambda = 570$ nm in the forward direction with low radiation pattern in the backward direction. At the second peak of 670 nm, the antenna still radiates effectively in forward direction with directivity higher than 10, and the backward radiation increases as shown in the inset of Fig. 3(a) which represents the 3D angular distribution of the radiated pattern P(⊖, Ø). This is compatible with that obtained for spherical nanoantenna reported in [5]. Fig. 3(b) shows the simulated directivities of the hybrid nanoantenna and spherical dielectric design [5] at $\lambda = 500$ nm. Further the directivity of the dielectric cylindrical nanoantenna at $\lambda = 570$ nm is also shown in Fig. 3(b). In this study, the geometrical parameters of the dielectric cylindrical design are the same as the proposed design. It may be observed from this figure that the radiation pattern of the hybrid nanoantenna is more directive at the studied wavelength than the dielectric nanoantennas. Furthermore, the suggested hybrid nanoantenna exhibits low back lobe level.

It is worth noting that the hybrid design of each element with plasmonic core (Ag) and a dielectric shell (Si) can enhance the directivity of the nanoantenna. The core-shell design can be thought as more efficient alternative to dielectric nanoantenna counterparts. The proposed design combines the advantages of plasmonic nanoantennas, with high directivity and high radiative decay rate, along with the dielectric nanoantenna merits of high efficiency associated with high directivity. The excitation of strong plasmonic modes is due to the ability of metallic nanoparticles to localize and increase the optical field intensity at nanoscale [15]. In addition, the dielectric nanoparticles with magnetic and electric modes exhibit low dissipative losses within the visible region [5], [28]. Hence, the supported modes are considered potentially appropriate for light control through manipulating the scattering properties [27]. The dielectric shell material (silicon) exhibits a strong magnetic dipole mode due to the excitation of a specific mode inside the nanoparticles with circular displacement current produced by the electric field [29]. The magnetic field oscillating up and down inside the particle seems similar to a “magnetic dipole” [30]. The excitation of such magnetic mode inside the nanoparticles is analogous to that of split-ring resonators [31]. However, the dielectric nanoparticles

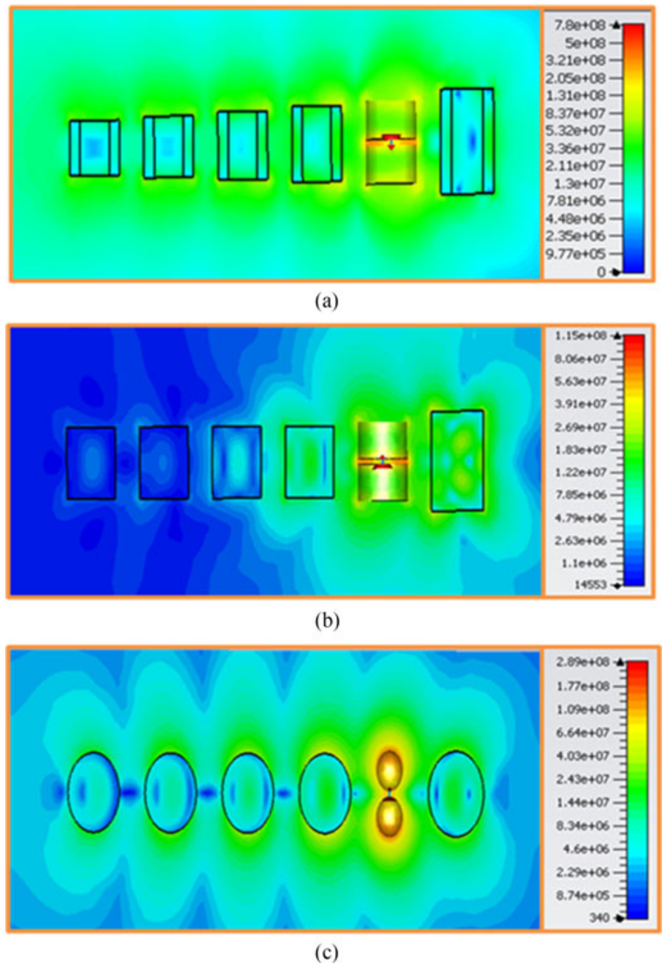

Fig. 4. Field intensity supported by the (a) suggested hybrid design, (b) cylindrical dielectric, and (c) spherical dielectric nanoantennas.

have much smaller losses than the ring resonators and can thus shift the magnetic mode wavelength down to optical frequencies [32].

Fig. 4 shows the TE field profiles around the hybrid cylindrical nanoantenna, and cylindrical and spherical dielectric nanoantennas at wavelength of 500 nm. It is found that the cylindrical shape of the suggested nanoantenna can play an important role in the directivity enhancement due to the homogenous distribution of the supported field intensity. Alternatively, the spherical nanoantenna [33] shows an inhomogeneity over the field intensity distribution as confirmed by the field profile shown in Fig. 4. It may also be noted from this figure that the hybrid nanoantenna has a uniform field distribution with maximum intensity of 7.67×10^8 V/m, which exceeds that for the dielectric nanoantenna (2.89×10^8 V/m) with non-uniform field distribution and that of the cylindrical dielectric nanoantenna with maximum intensity of 1.15×10^8 V/m.

Fig. 5 exhibits the power flow for the suggested nanowire core-shell nanoantenna, cylindrical dielectric and spherical dielectric nanoantennas. The maximum power flow for the hybrid nanoantenna is equal to 7.2×10^{16} V.A/m^2, which is greater than those of the spherical dielectric nanoantenna (1.4×10^{15} V.A/m^2) and cylindrical dielectric nanoantenna (2.7×10^{13} V.A/m^2). Such enhancements in the field profile and power flow of the suggested design are attributed to the combination between magnetic and plasmonic modes generated by metallic and silicon materials in the hybrid design. The enhancements in the transmitted or received power readily reduce the dissipated power and, hence, improve cost effectiveness.

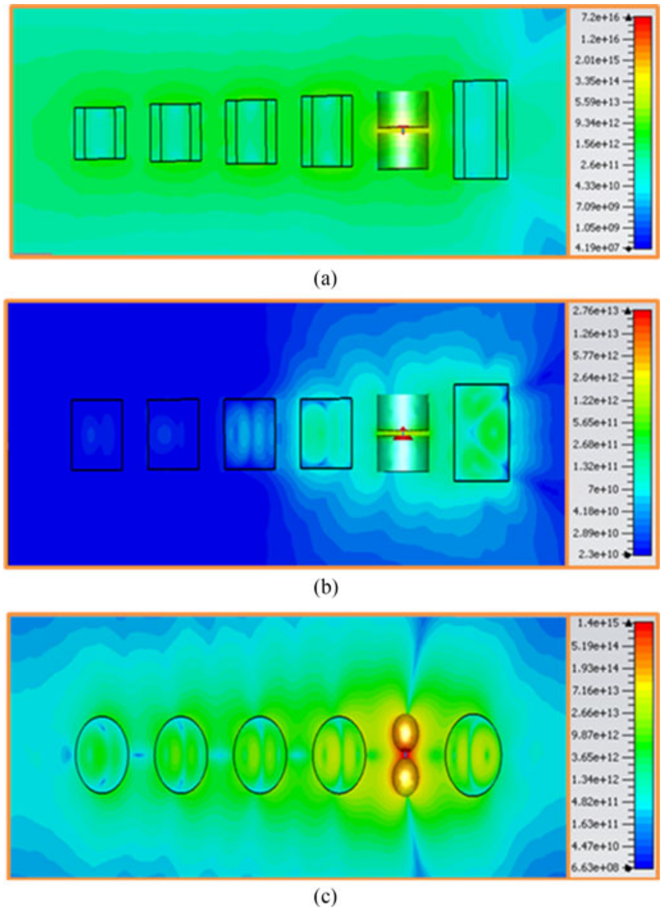

Fig. 5. Power flow of the (a) suggested hybrid design, (b) cylindrical dielectric, and (c) spherical dielectric nanoantennas.

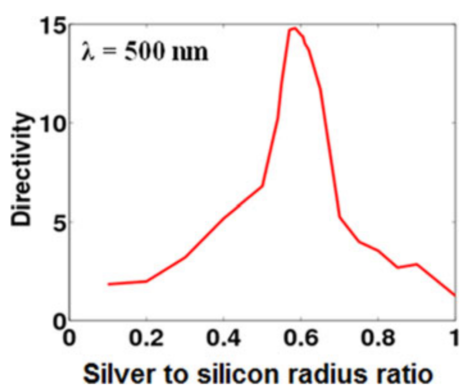

Fig. 6. Directivity as a function of the ratio between the core and cladding radius.

One of the main advantages of the suggested core-shell nanowire design is the three design parameters, i.e., the height, core radius, and cladding radius, that can be tuned to achieve high directivity. The directivity of the proposed design as a function of the ratio between the core and cladding radius is depicted in Fig. 6. By tuning the radii of the core and clad of the nanowires; the directivity of the nanoantenna is enhanced to its maximum value of 14.8 at a ratio of $R_2/R_1 = R_4/R_3 \sim 0.6$. This particular design has a director with a core radius $R_4 \sim 42\,\text{nm}$

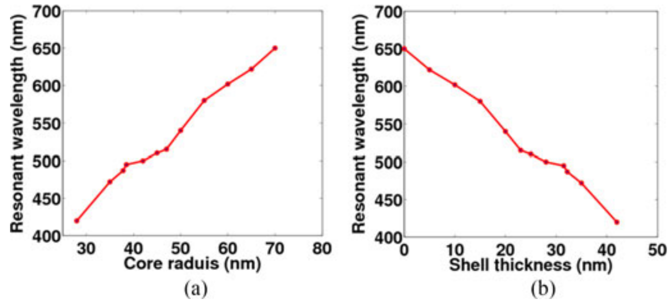

Fig. 7. Variation of the wavelength with (a) core radius and (b) shell thickness of the proposed design, respectively.

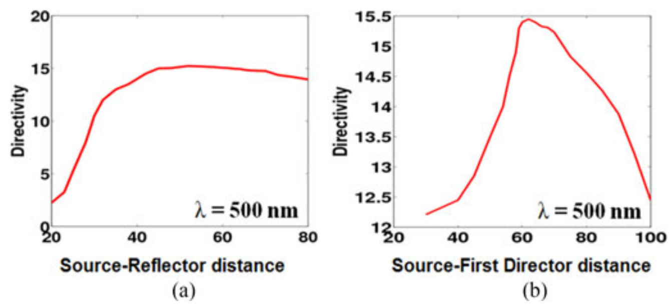

Fig. 8. Variation of the directivity of the proposed design with (a) the distance between reflector and feed element and (b) the distance between the first director and the source.

and shell thickness of ∼28 nm. Further, the reflector illustrates a resonance at a core radius $R_2 \sim 45$ nm with a silicon cladding of ∼30 nm.

The effects of the core radius and shell thickness for the proposed design are investigated. Fig. 7(a) and (b) show the variation of the resonance wavelength as a function of the core radius (silver metal) and the shell thickness (Silicon), respectively. As the core radius increases from 30 nm to 70 nm the resonance wavelength is shifted toward longer wavelength of 650 nm. In addition, the desired wavelength of 500 nm can be obtained at core radius of ∼42 nm, as shown in Fig. 7(a). However, the resonant wavelength is shifted toward shorter regime by increasing the silicon shell thickness and the preferred wavelength is obtained at a shell thickness of ∼28 nm as revealed from Fig. 7(b). Therefore, the core radius and shell thickness can play an important role in controlling the resonant wavelength of the radiation of the proposed nanoantenna design.

To enhance the directivity of the hybrid core-shell design, the other geometrical parameters of the investigated nanowire Yagi-Uda nanoantenna have been analyzed thoroughly. The effect of the distance between the feed element and the passive elements (reflector and directors) is primarily considered. Fig. 8(a) and (b) display the directivity versus the distances between the dipole source and the reflector and the first director, respectively. The main function of the reflector element in the Yagi antenna design is to reflect the backward radiation to the specific direction of propagation. Furthermore, the directors apparently affect the forward directivity. The distance between the dipole source and the passive elements gives rise to an undeniable coupling effect [12]. A minimal distance between the reflector and the dipole source decreases the directivity of the nanoantenna due to the accompanying increase in the backward radiation lobes. As the distance increases, the coupling between the two elements decreases and consequently the directivity of the nanoantenna decreases. The optimal distance is equal to $D_1 \sim 52$ nm with directivity of ∼15.23 due to the strong coupling between the reflector and the feed element, along with the reduction of the backward radiation to a low level. On the other hand, the coupling between the dipole source

TABLE II
Optimum Hybrid Nanoantenna Parameters

Radius (nm)	Reflector		Directors	
	R_1	R_2	R_3	R_4
	85	53	80	50
L_f	160 nm			
L_d	144 nm			
Scaling factor (S)	0.9			
L_r	220 nm			
D_1	52 nm			
D_2	62 nm			
D_3	70 nm			

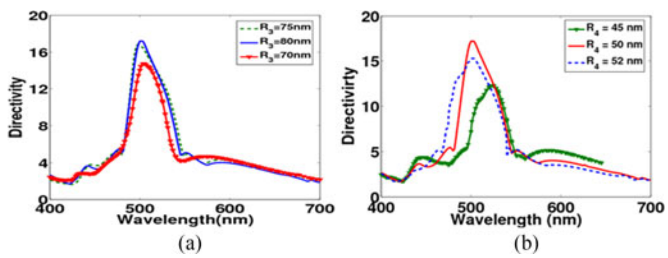

Fig. 9. Variation of the directivity with the wavelength at different values of (a) R_3 and (b) R_4.

and the first director largely depends on the distance between them, while the distance between the other directors is still kept constant at $D_3 \sim 70$ nm. The optimum distance between the feed and the first director is equal to $D_2 \sim 62$ nm, and the directivity is enhanced to 15.45, as shown in Fig. 8(b). This probably occurs due to the significant coupling between the feed and the first director combined with the oscillation of the first director, analogous to a dipole source [12].

The effects of the radii R_3 and R_4 for the core-shell nanoantenna are also discussed, while the other parameters are fixed at their optimized parameters listed in Table II. For dielectric nanoantenna, it is confirmed that the optimal director radius is equal to 70 nm, due to the supported strong magnetic field [5]. Fig. 9(a) shows the wavelength dependent directivity at different R_3 values. It may be noted from this figure that high directivity of 17.21 is achieved at $R_3 = 80$ nm due to the strong surface plasmon (metal) and the magnetic (dielectric) modes. The effect of the radius R_4 for the core-shell nanoantenna is also studied. It is found that the maximum directivity is obtained at $R_4 = 50$ nm at wavelength of 500 nm as shown in Fig. 9(b).

Fig. 10(a) and (b) depicts the directivity of the dielectric spherical nanoantennas [5] and the optimal hybrid nanowire antennas. Fig. 10(c) shows the wavelength dependent radiation efficiencies for the proposed core shell nanoantenna and the spherical dielectric design [5]. It is revealed from this figure that the reported nanoantenna design has greater radiation efficiencies than that of the spherical counterpart in the wavelength range from 425 nm to 650 nm. It is worth noting that the radiation efficiency of the proposed structure is equal to 0.51 at wavelength of 500 nm which exceeds that of the spherical dielectric nanoantenna reported by Krasnok *et al.* [5] with an enhancement of 53.6%.

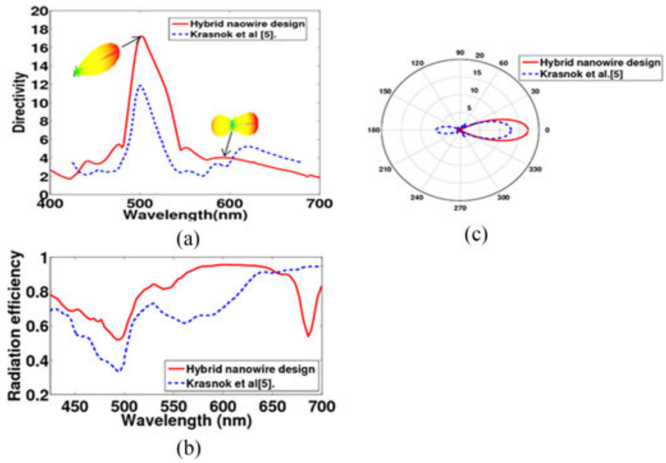

Fig. 10. (a) Variation of the directivity of the hybrid core-shell nanoantenna and the spherical dielectric design [5] with the wavelength, (b) simulated directivity pattern of the optimum design and the spherical dielectric nanoantenna [5] at wavelength of 500 nm, and (c) variation of radiation efficiencies with the wavelength for the core-shell nanoantenna and the spherical dielectric structure [5].

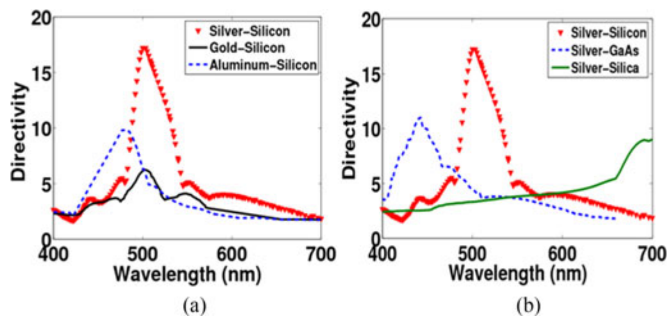

Fig. 11. Variation of the directivity of the core-shell nanoantenna with the wavelength at (a) different core materials and (b) different shell materials.

The optimal structure of the investigated core-shell-Yagi-Uda-nanoantenna consists of five elements and the geometrical parameters are listed in Table II. The directivity of the proposed structure is enhanced to 17.21 at wavelength of 500 nm, which exceeds that of the spherical dielectric nanoantenna reported by Krasnok *et al.* [5] with an enhancement of 43.41%.

The effect of the material type of the suggested design is indicated in Fig. 11. Fig. 11(a) shows the effect of other plasmonic materials such as gold and aluminum on the directivity of the optical radiation for the core shell nanowire nanoantenna. It may be noted from this figure that the directivity reaches $\sim$6 for the hybrid design (Gold–Silicon) while the Aluminum core increases the directivity to $\sim$9. However, high directivity of $\sim$17.21 can be achieved by using silver core with silicon shell. Fig. 11(b) depicts the effect of the dielectric shell material for the proposed design with silver core. It is revealed from this figure that the GaAs shell offers directivity of $\sim$11, while the Silica shell has directivity of $\sim$7 at a wavelength of 700 nm.

4. Fabrication Tolerance Analysis

As significant perturbations may occur in the fabrication processes at nanoscale, tolerance study is performed for hybrid nanoantenna structures. The sensitivity of the nanoantenna performance is calculated through introducing minor changes to the structure dimensions (L_f, R_1, and R_3).

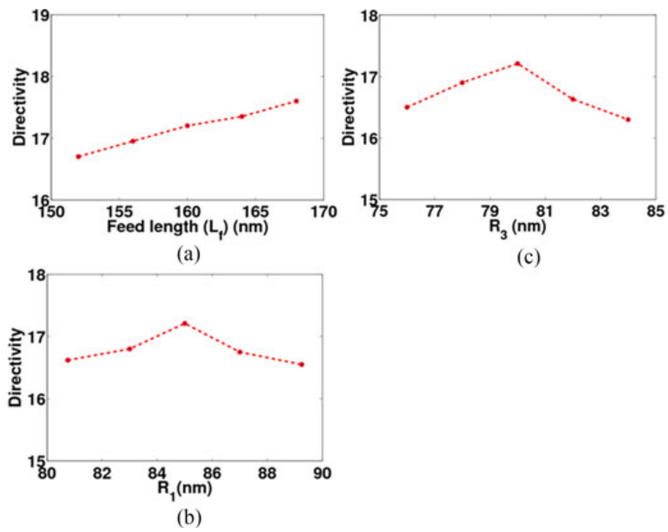

Fig. 12. Variation of the directivity with (a) the feed length L_f, (b) R_3, and (c) R_1.

At certain optimum values ($L_f = 160$ nm, $R_1 = 85$ nm, $R_3 = 80$ nm) the tolerance of a specific parameter is analyzed, while the other dimensions of the design are held constant at their optimum values. The variation of the directivity and the studied dimensions L_f, R_3, and R_1 are shown in Fig. 12(a)–(c), respectively. It is evident from this figure that the proposed design has a tolerance of $\pm 5\%$; at which the directivity is better than 16.3. From the above results, the proposed nanoantenna design offers high sturdiness for fabrication limitations.

5. Conclusion

In this paper, a novel design of hybrid Yagi-Uda nanowire antenna is introduced and analyzed. The 3-D finite integration technique (FIT) is used to simulate the proposed design. The investigated nanowire antenna consists of five elements; each element has a silver core with a silicon cladding. It is found that the core-shell-Yagi-Uda-nanoantenna has ultra-high directivity of 17.21 at wavelength of 500 nm with only four directors. Moreover, the proposed design exhibits lower dissipation losses. Further, it enhances the transmitted and the received powers and optimizes the far field radiation pattern. This enhancement is attributed to the surface plasmon and magnetic modes supported by the proposed design. The dielectric shell is in charge of the magnetic mode while the silver core, exhibits a strong surface plasmon mode. In addition, the cylindrical nanowires enhance the directivity due to the homogenous field distribution around the reported cylindrical nanoantenna.

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