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Chapter

Plasmonic Optical Nano-Antenna for Biomedical Applications

Rasha H. Mahdi and Hussein A. Jawad

Abstract

Plasmonics attract significant attention of the researchers due to Plasmon's surpassing ability to match free space electromagnetic (EM) excitation into the nano-scale size and conduct the light-tissue interaction in this scale. Plasmonic nano-antennas (PNAs) is a coupling of EM waves into Localized Surface Plasmon Resonance (LSPR) which is considered as an interesting subject for theoretical and experimental study. This presents a new concept of the confinement of light in subwavelength scales with huge local fields which can generate very high near field intensities because of their LSPR. The generated field is invested in various applications that are depending on near field enhancement produced by plasmonic optical nano-antennas (PONAs) such as Surface-Enhanced Raman Spectroscopy (SERS), biosensing, spectral imaging and cancer treatment. Bowtie shape PNAs (PBNAs) can transfer the light field efficiently by converting the light from external space into a subwavelength spectral region with the improvement at an optical wavelength in a tiny area between its antenna arms. The local EM field production in a gap area is the main reason to suggest PBNAs shape if the frequency of the incident EM waves coincide the structural resonance peak so it is acting as a tunable hot spot.

Keywords: plasmonics, laser cancer treatment, biomedical applications

1. Introduction

The back bone of numerous applications in the recent years is the plasmonic nano-antennas especially in the optical spectral regions due to their unique properties, as high enhancement and subwavelength confinement of the electrical field. One of the attractive application is the treatment of the cancer cells where the diffusion of heat could be controlled via plasmonic nano-antennas and hence the temperature is confined in the diseased tissue. Nano-antennas are consisting of adjacent metallic nano-particles with nano-scales gaps (in particular the bowtie shape) which have excessively strong field confinement and enhancement in the gap region. The generated field is invested in various applications that are depending on near field enhancement produced by plasmonic optical nano-antennas (PONAs) such as cancer treatment. The heat produced and the thermal diffusion in the plasmonic structure are not richly investigated might be due to the shortage in the experiments. Vigorous potentials are conducted into the development of new techniques for the controlled temperature at the nano-scale and the destroying cell by the temperature rise due to the converting heat is also included.

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In this chapter we try to high light on the important aspects of the interaction of laser light with proposed cancer cells. A case study was designed and studied represented by a plasmonic bowtie nano-antenna. First of all, we have to design a suitable cell of nano-antenna considering the dimensions in nano scale. The second step is to select the shape because it represents the enhanced field source in addition to an appropriate noble metal due to the application of plasmonic bow-tie nano- antennas is conducted inside the human body. The wavelength of the laser used should be selected depending on the resonance frequency because the absorption is regarded the first step of the plasmonic generation. The field distribution is quite important to kill the diseased cells so, the angle of laser incidence and the distance to the tissue play the essential role in the effective process. The virtual tissue is irradiated by two laser wavelengths (532, 1064) nm through a single bowtie nano-antenna, The absorption of EM field that is transferred to heat in the human body depending on the incident EM power density is measured via SAR. It is written as Eq. (1) [1].

$$SAR = \sigma |E|^2 / 2\rho(Kg / \mathrm{w}) \tag{1}$$

Where:
σ = conductivity of the tissue-simulating material (S/m).
E = total Root Mean Square (RMS) field strength (V/m).
ρ = mass density of tissue-simulating material (kg/m3).
From the thermal energy deposited on the proposed tissue, the temperature elevation could be estimated as the following equation:

$$dQ = \rho\, V\, C\, dT \tag{2}$$

Where:
Q = the thermal energy (J).
V = the volume (m3).
C = the specific heat (J /K. kg).
T = the temperature in Kelvin (K).
Both sides in the equation could be divided by (ρ V dt), then the terms are rearranged, so the following equation could be written as:

$$(dQ / dt) / \rho\, V = C.dT / dt \tag{3}$$

The specific absorption rate and the temperature elevation detection via the time period calculation are the main considered parameters. Finally, the main conclusions are extracted from the obtained results of the case study.

2. Plasmonics nano-antenna

The optical field could be transformed into localized energy via a structure called optical nano-antennas (ONAs). Their structures have an ability to control and manipulate the optical field at subwavelength scales [2].

ONAs require engineering accuracies of the characteristic dimensions down to a few nano-meters while about to the wavelength scale in other antennas [3–6].

However, this downscaling holds the technological challenges of nano-scale antenna engineering [6, 7]. The antenna performance can be strongly enhanced by plasmon resonances that lead to high and confined fields. The optical excitation of ONAs with a suitable wavelength can produce very high near-field because of their LSPR [4].

The interaction of an intense electromagnetic field with electrons ejected freely at the interface between dielectric/metal results in a quantum electromagnetic phenomenon called surface plasmon resonance (SPR). plasmonic is a field that deals with SPR. The interesting potential for engineering many devices and patterns involving nano-photonic devices are based on plasmonic nano-structures.

Plasmonic nano-antennas (PNAs), are able to controlling and confining EM field at the nano-scale. The performance evaluation of PNAs is depending on two important parameters, the absorption of the light and field improvement locally. A wide research areas invest the high light absorption, such as thermal emitters, solar thermal applications, thermal photoluminescences, and sensors. The improved electric fields at resonance wavelength can modulate the optical properties in the vicinity of molecules, so that, enhancing their light-matter interactions [8–10].

The tuning of the plasmon resonance for both absorption and emission to the excitation or the emission of species is the interesting research recently. The exciting EM field is enhanced several order of magnitude due to the production of what so-called hot spots when perfect nano-structures are designed. The structures working at plasmonic resonances open the ability to implement antennas working in the visible. The hot areas could be used to excite the effects at nonlinear regime so to match the EM field effectively. SERS and tip-enhanced Raman spectroscopy are the practical techniques that show the influence of such hot areas to observe the emitters with its sensitivity down to a single molecule [11].

The construction structure of PNAs is depending mainly on putting a gap at the sub-wavelength scale between two metallic areas, are gained distinguishable importance. This is mainly because of the hot spots in PNAs produce intensive EM field in nano-size overcoming the restriction of the diffraction. The confinement of the light field by BNAs is observed to be several order of magnitudes in the nano-scale smaller than the incident wavelength, as improved by the dimensions of the gap [12].

The resonance wavelength decisively depends on the shape, dimensions, and material of the antenna, a numerous variation of plasmonic antenna structures published proposed, such as bowties, nano-rings, nano-rod, and Yagi-Uda antennae. The sharp resonance wavelengths with narrow-band spectra with sharp are a major challenge for applications that require devices operating over a wide range of frequencies. For example, antennas used to improve energy harvesting efficiency of photovoltaic devices. Broadband PNAs are also highly wanted for SERs, fluorescence enhancement, and higher harmonic generation, which are multi-wavelength and broadband in nature [13].

2.1 Metal nano-antennas

The intensity of the light, the dimensions of the components, and the material used are the essential parameters that produce plasmons excited by optical frequency. The suitable matters for this type of excitation are noble metals (i.e., gold (Au), silver (Ag), copper (Cu), and aluminum (Al)) so result in an important enhancement of the design and devices.

The nano-structures of metals with around area included in any design of optimized parameters need mainly the optical properties of PNAs especially in the medical field. Among many metals, gold is a perfect metal against high-temperature oxidation with the best plasmonic characteristics and especially suitable for biocompatible applications.

Distinguished spectroscopic features (spatial, spectral) are observed in noble metal nano-antennas (MNAs) such as Au NPs and Ag NPs. MNAs have those features resulting from the oscillations of electrons collectively in the conduction band, which is LSPR [10].

MNAs can confine and improve near IR and visible field in superficially by the excitation of LSPR. The 'EM hot region (spot)' that could be created on the nano-antennas has excessively utilized the absorption of light locally leading to an increase the weak intensity in the nonlinear optical process [14].

Au nano-particles (Au NPs) could effectively absorb IR and visible field energy in quite concentrated sizes, getting them properly controllable heat source in subwavelength size. In addition to the great importance the mechanism of those phenomena to be investigated, the capability to generate point like heat nano-heat encourage a broad area of research in physics, chemistry, and biology. The aforementioned properties of Au NPs especially as a nano-sources are promising researchers in the catalysis at nano-size, photonics, and in the field of medicine for cancer cells destroying photothermally [15].

3. Heat generation in nano-antenna

PNAs cause an exaggerated heat produced in the metal after the excitation of the external light source, producing a side hot areas—i.e., the elevation of the temperature in a restricted region which is a mainly undesirable effect in various research namely spectroscopy, sensing, and optical signal processing. Localized heat of PNAs, in another hand, is very useful in a group of applications such as nano-engineering, cancer treatment, nano-manipulation, hot vapor generation, and catalysis [14].

The local temperature elevation of MNAs is quite low thermal radiation in the mid-to-far IR wavelength spectral region. In addition, if (the mean free path) of the substrate materials is larger than the nano-antenna size, the heat converted the volume of metal volume may be reduced [16]. It is well known that the metals in nano-size create regional temperature gradients after external light exposure, quite enough to generate subwavelength areas of super-heated water surrounding the species [17].

Photo-induced heating of nano-antennas can vary their geometry because of the metal melting. The melting process can minimize the nano-range properties so, directly nano-antennas becomes nano-spheres if temperature increment is established. The variation of the morphology may affect on the antennas' spectral response and can decrease the near-field generation. The melting temperature of metal can take place at higher surface melting temperatures of nano-antennas [18, 19].

The pioneering author is previously shown that the structures of hybrid plasmonic have good selectivity and huge improvement of the near-field intensity due to effective trapping with re-cycling of photons in near IR and visible in photonic modes [20–22].

The IR thermal radiation could be produced and enhanced by the selection of the optimum parameters of materials and the dimensions regarding the geometry on a range at or under the emitted thermal peak resonance wavelength [14]. The convective and radiative cooling represent other ways to diffuse heat intensity from nano-sizes, where became effective if the thermal conductivity is disturbed because of the particles in the nano-size [23].

4. Specific absorption rate

The extension result of the EM field is the elevation temperature of the tissue in a limited region caused by the generated heat which could affect on the biological system. The heat diffusion and its influence on the tissue are specified by the Specific Absorption Rate (SAR). SAR magnitude can not increase above the level of irradiation which becomes harmful. SAR magnitude is depending mainly on various factors such as the position of the antenna related the human tissue, the intensity field of the antenna, and the power.

The specific absorption rate (SAR) is an indication tool of absorption where the EM field exposure in the human body could be estimated. SAR is mainly used to measure the absorbed power in the tissues after irradiation by external field so that it gets the heat of tissue to be increased. The biological tissue heat could be checked via a safe method which is mainly depending on measuring the temperature elevation in tissues. It is mentioned that the temperature and SAR are evaluated in the human tissues so the precaution measures are verified. SAR is a function of many factors. Those factors affect on the absorption of EM field. SAR variations are depending on the properties of the wave, properties of the body and environment properties. Regarding the properties of the wave, the extent of SAR changes is depending directly on the features of the signal, such as frequency and polarization. In another side the dependence with the tissue human body, the SAR value depends on the type of tissue (e.g., geometry, size, age, and dielectric properties) and tissue orientation/exact location (e.g., the situation of the body; front or back incidence). SAR, in addition, depends on the exposure states, e.g., environmental exposure (indoor and outdoor) and influences of other objects in the field near the exposed body [24].

It is important to understand SAR calculation with respect to averaging design. There are two procedures to accomplish SAR calculations: first is point SAR, and second is averaging SAR (i.e., mass or volume). Point SAR is the value regardless of the averaging of the mass and the maximum SAR of all the grid cells is provided. When the absorbed power in each grid divided by grid mass, the point SAR is evaluated. While in the averaged SAR, a cube of known mass, e.g., 1 or 10 g, is utilized for every point, then the loss of the power density is integrated on this region. Then, the power loss in the integral form is divided by the mass cube [1, 24].

Because the electric field is usually not spatially uniform, SAR is averaged over a volume of tissue regarding the type of the source. It is useful to mention that the electric field is not fixed in time, so that, the probe is used for short-term time-averaging [1].

5. Time period estimation

The temperature is elevated in human tissues due to the absorption of power from EM fields. An irreversible damage of the tissue can take place due to the absorption of high power. The dielectric and thermal features of the proposed tissue model are used to evaluate the relationship between the temperature and the point SAR, it could be estimated considering the equation of heat (2) [25].

The SAR value is represented in the left side, so that the thermal distribution in tissues for a period of (Δt) can be determined.

It can rewrite Eq. (4) as:

$$F=P/A. \tag{4}$$

It is worth to mention that the short time period is quite important in the treatment of the diseased tumor cells because of the generated heat does not dissipated to the surrounding healthy tissues, for this reason the calculated time period in this study does not possible unless using the laser either in pule mode or in chopped mode.

6. Design of nano-antenna

From the various type of optical nano-antenna, the bowtie shape is the preferred choice in this study, as compared with a dipole [26]. Plasmonic BNAs is usually designed due to the confinement of the electric field in the gap region, working at higher frequencies, and keeping the whole size much smaller (nano-meter) [9]. Regarding the sharp tips of the two arms of the bowtie antenna, the group and phase velocities of surface plasmonic waves decrease with the distance of propagation and finally become zero [27]. BNAs are expected to possess a relatively broad bandwidth because they represent the two-dimensional analogue of a biconical antenna [28]. The localized plasmonic near-field, which is highly sensitive to the refractive index of its surrounding medium can be tuned by adapting the nano-structure shape. Geometrical parameters such as size, gap distance, height, and bowtie apex angle have a direct effect in the LSPR [29].

7. Single unit plasmonic bowtie nano-antenna

Bowtie shape PNAs (PBNAs) can transfer the light field efficiently by converting the light from external space into a subwavelength spectral region with the improvement at an optical wavelength in a tiny area between its antenna arms.

First of all, initial dimensions are selected to design primary bowtie shape nano-antenna by sitting the length of nano-antenna is (L), the width is (W), the thickness is (T), the apex width is (A), the gap width is (G) and the bowtie apex angle is (Θo) [30], as shown in **Figure 1a**.

The bowtie structure is normally illuminated by linearly polarized waveguide excitation source along the x-axis (x-polarization). The surrounding environment of the design structure is assumed to be air. as shown in **Figure 1b**.

8. The proposed tumor tissue model

The proposed tumor represents cancer cells in the skin tissue located in the center of the skin structure as shown in **Figure 2**.

The thermal properties of the tissue are listed in **Table 1**. In addition, the dielectric properties of the tissue play an important role in the investigation of the

DOI: http://dx.doi.org/10.5772/intechopen.105458

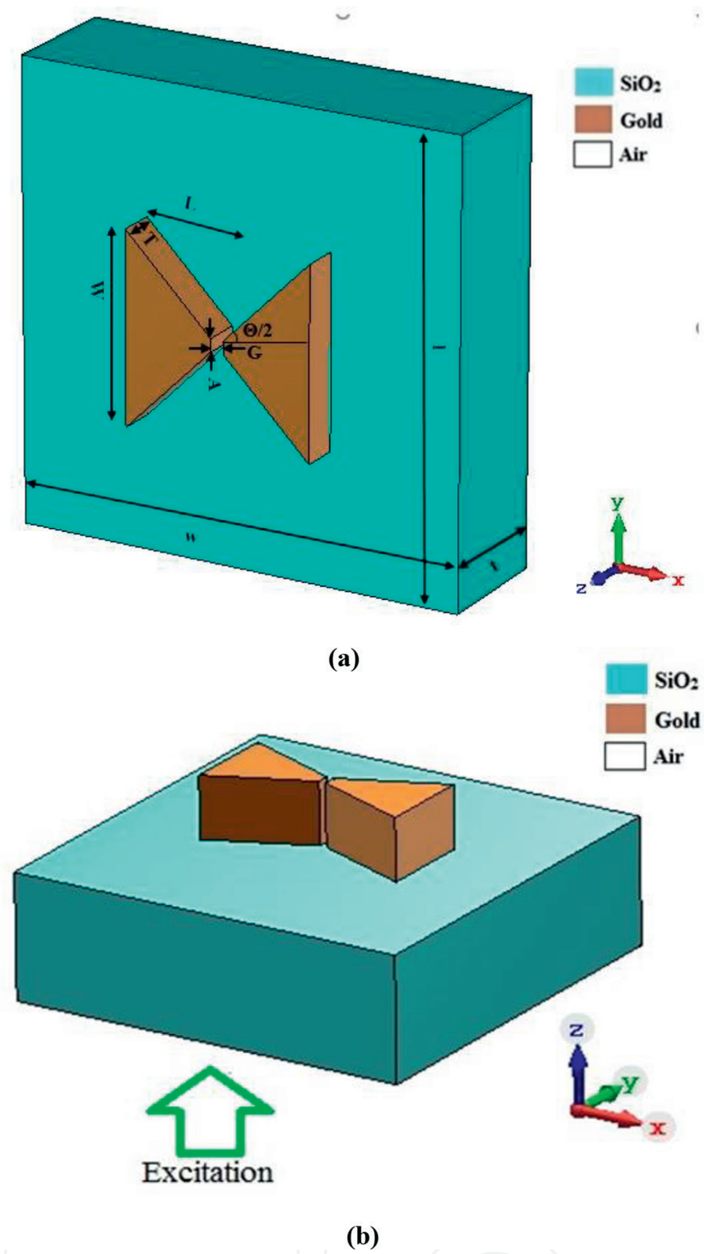

Figure 1.
(a) Schematic diagram of single 3D plasmonic nano-antenna with dimensions of the length of nano-antenna is (L), the width is (W), the thickness is (T), the apex width is (A), the gap width is (G) for the gold and the length (l), width (w), thickness (t) for the SiO2, and (b) the direction of excitation.

propagation characteristic of the plasmonic optical nano-antenna. These properties are mainly depending on tissue type and the wavelength of interest.

8.1 Exposing the tumor to the designed nano-antenna

The designed tissue is subjected to the plasmonic nano-antenna (single and an array) radiation at different distances, the resulted pattern is shown in **Figure 3**.

The designed structure was illuminated normally by a waveguide source linearly polarized along the x-axis as shown in **Figure 3**. The proposed tissue is located in the upper edge of the antenna and centered in front of the gap of the nano-antenna. The structure is surrounded by the air.

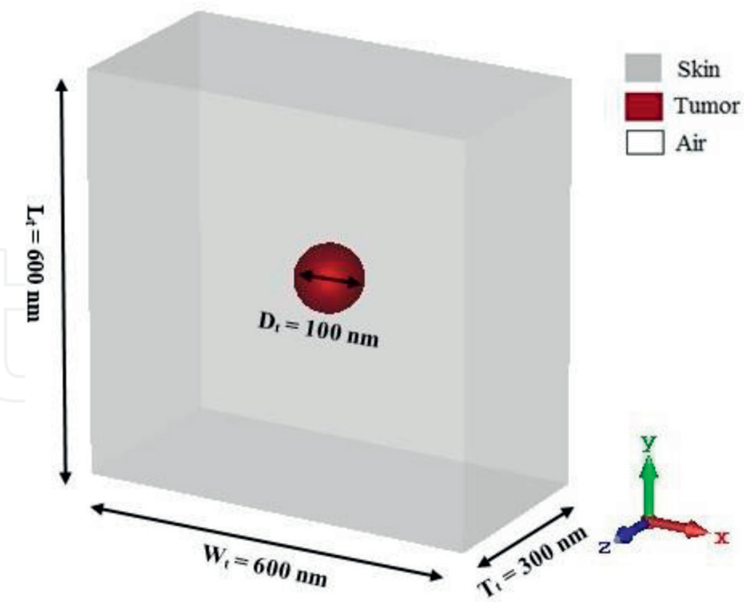

Figure 2.
3D schematic view of the tumor embedded in the skin tissue. The dimensions are (L = W = 600 nm and T = 300 nm).

Tissue	Thermal conductivity K (W/m)	Specific heat C (kJ/K/kg)	Mass density ρ (kg/m3)
Skin	0.2	3.6	1200
Tumor	0.5	3.6	1050

Table 1.
The properties of the tissues.

9. Specific absorption rate calculations

The estimation of the temperature distribution of any tumor embedded in a tissue exposed to a light source is quite complicated due to the nature and the location of tissues. In the present study, the time of reaching the temperature to be fair enough for destroying the diseased cells is estimated through the calculation of SAR.

9.1 Specific absorption rate at 532 nm for single nano-antenna

The optimized single NA working at resonance wavelength 532 nm is located at different distances from the tissue (100, 200, 300 and 400) nm to calculate the SAR for each as illustrated in **Figure 4a–d**. The point SAR inside the proposed tissue are (1.83 × 1011, 1.19 × 1011, 8.22 × 1010, and 4.72 × 1010) W/kg for distances (100, 200, 300 and 400) nm respectively. It is observed clearly that the SAR reduces with increases the distance because the reduction of the strength of the receiving far-field. The field is concentrated in the center of the tumor which means that the surrounding tissues are not affected by the field.

The behavior of SAR related to the distance from the proposed tissue at the wavelength of 532 nm for single NAs is shown in **Figure 5**. The SAR is increased with closer distance and the maximum value of SAR is detected for single unit.

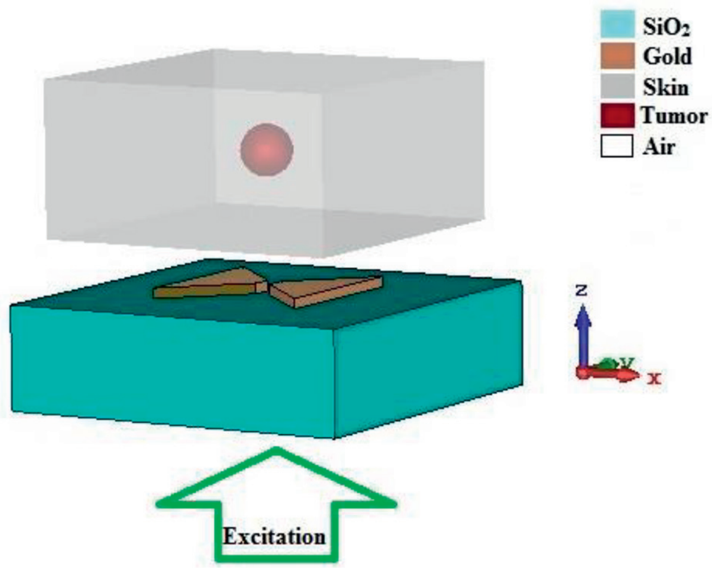

Figure 3.
The final pattern of bowtie nano-antenna in front of the designed tissue.

9.2 Specific absorption rate calculations at 1064 nm single nano-antenna

Figure 6a–d shows the distribution of the field in the tissue after subjecting to single NA at 1064 nm for various distances (100, 200, 300 and 400) nm. The point SAR inside the proposed tissue could be calculated. The maximum values of SAR are (2.28 × 1011, 1.17 × 1011, 8.49 × 1010, and 8.11 × 1010) W/kg for distances (100, 200, 300, and 400) nm respectively. It is noticed that the point SAR value is not varied clearly at this wavelength.

Figure 7 shows the behavior of SAR as a function of different distances at the wavelength of 1064 for single NAs. Similar behavior is detected for both wavelengths but it is noticed that sharp reduction from single to an array structures.

It is obvious that the distribution of the far-field in the tumor is varied for two resonance wavelengths (532 and1064) nm where the field is appeared out the tumor in the case of 1064 nm. This distribution may affect on the healthy surrounding tissues which are not preferred in this type of application although the strength of the field is suitable. In addition, it is well observed that the SAR increases with the closest distance.

10. Time period estimation

The temperature elevation in the irradiated tissues could be estimated easily related to the SAR calculations owing to Eq. (1). It is noticed from this equation that the temperature elevation in the tissue is depending mainly on the time period of exposing to NAs for a certain SAR, so the time period should be selected carefully to verify the wanted temperature for tumor cells killing.

10.1 Time period estimation in tumor tissue at single nano-antenna

The main goal of the treatment of the tumors is the temperature rise over the normal level to cause cells damage which could be estimated by (60°C). **Table 2**

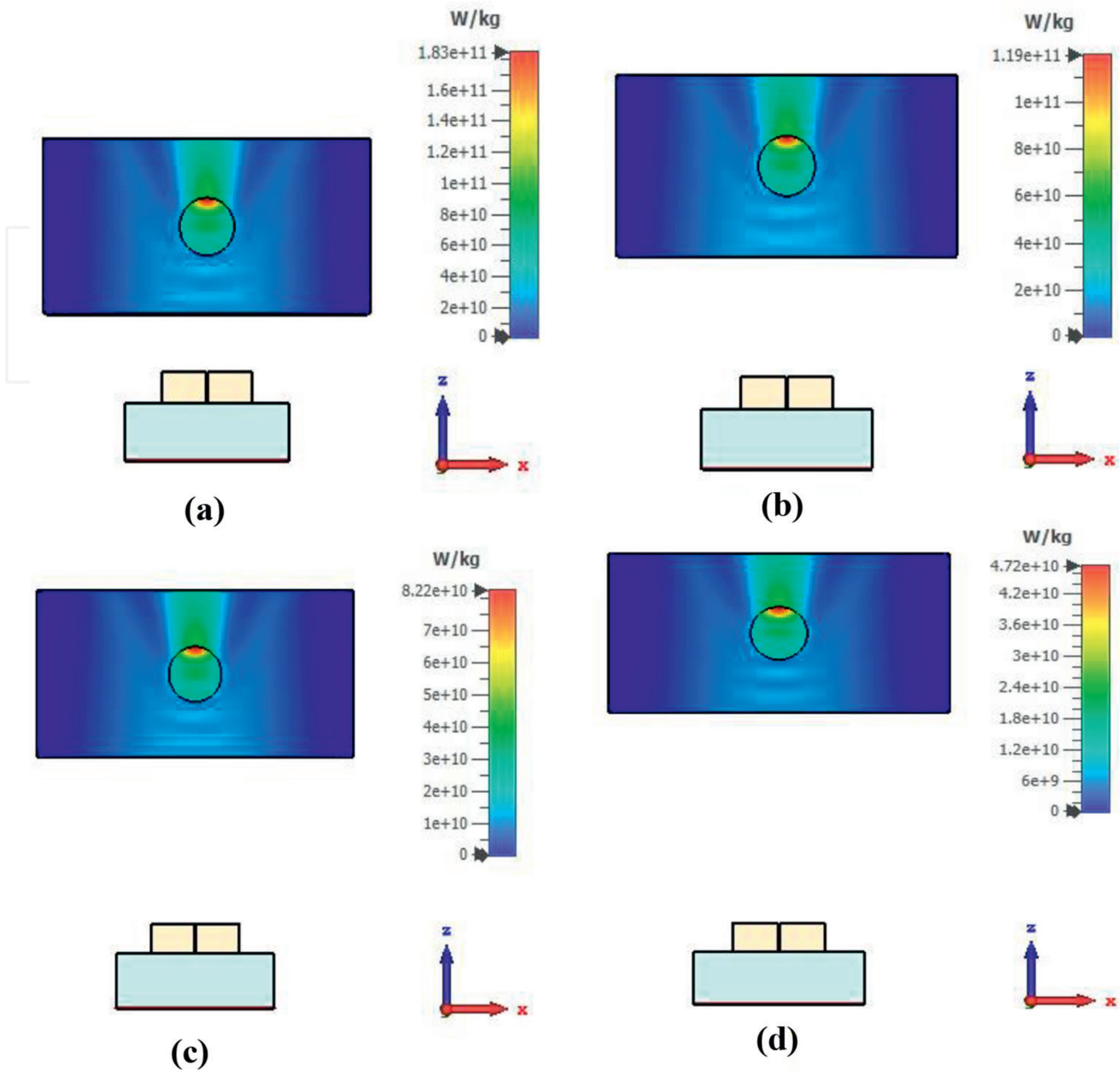

Figure 4.
The calculated SAR in the proposed tumor tissue exposed to a single NA at 532 nm for different distances. (a) 100 nm, (b) 200 nm, (c) 300 nm, and (d) 400 nm.

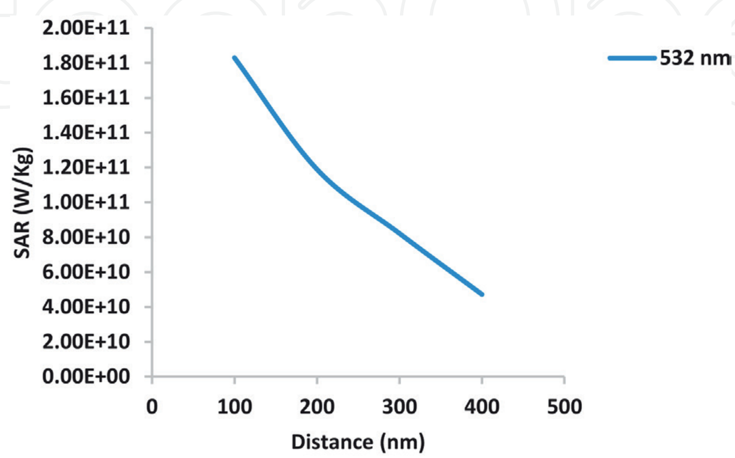

Figure 5.
Specific absorption rate as a function of the distance from the tissue at single unit for 532 nm.

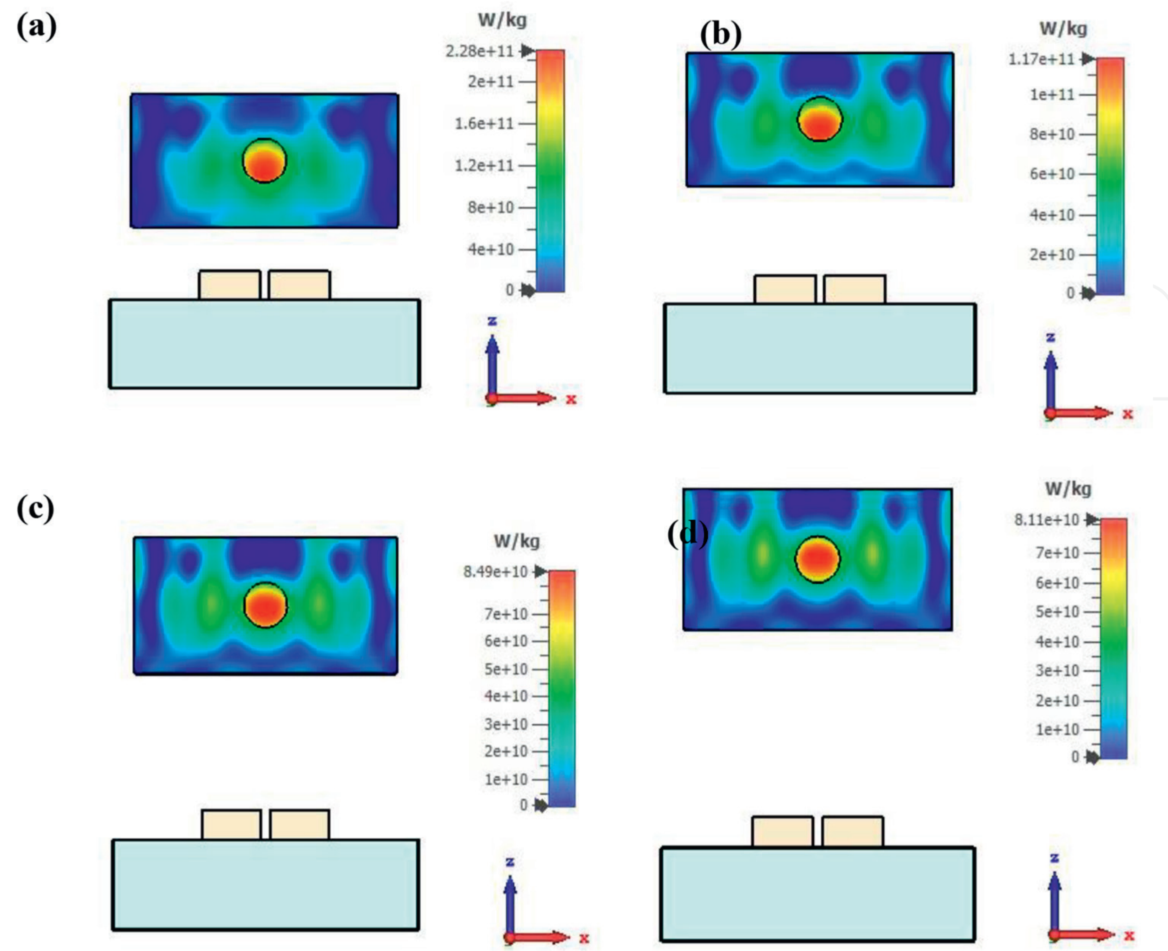

Figure 6.
The calculated SAR in the proposed tumor tissue subjected to single NA at 1064 nm at different distances (a) 100 nm, (b) 200 nm, (c) 300 nm, and (d) 400 nm.

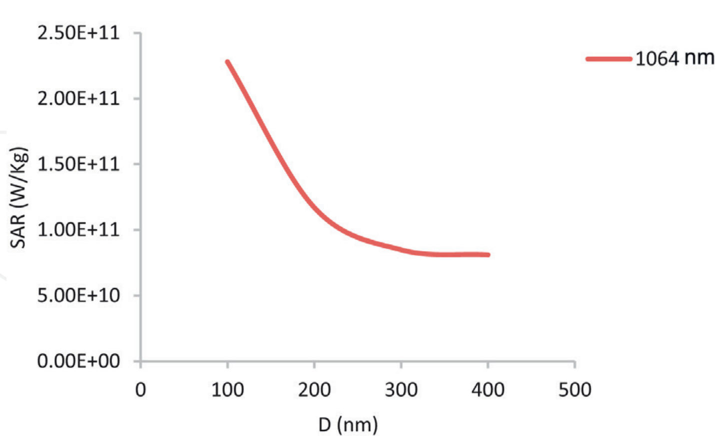

Figure 7.
The specific absorption rate as a function of the distance from the proposed tissue at 1064 nm for single unit.

represents the time period estimation to attain the required temperature in the proposed tumor tissue for single NA at two wavelengths (532 and 1064) nm for different distances (100, 200, 300 and 400) nm from the tissue. It is clear that the time period is shorter for closer distance from the tissue for both wavelengths while it shortest for

Distance D (nm)	Time period (μs)	
	532 nm	1064 nm
100	6.55	5.26
200	10.1	10.2
300	14.6	14.1
400	25.4	14.8

Table 2.
The calculation of the time period in the proposed for distances (100, 200, 300 and 400) at two wavelengths (532 and 1064) nm for single nano-antenna.

longer wavelength (1064 nm). It is observed from the results that the time period is varied related to the field distribution in the tissue and how much regular and hence for SAR calculation.

It is worth to mention that the short time period is quite important in the treatment of the diseased tumor cells because of the generated heat does not dissipated to the surrounding healthy tissues, for this reason the calculated time period in this study does not possible unless using the laser either in pulse mode or in chopped mode.

The optical plasmonic nanoantenna proves high ability to destruct the tumor tissues especially the cancer cells due to those antennas are considered as a hot point source which means that the desired tissue could be destroyed without affecting the surrounding healthy tissues. Our purpose is to estimate the thermal distribution in the tissue at different distances from the nanoantenna. The bow tie shape of plasmonic nanoantenna is selected because in the sharp tip the group and phase velocities of surface plasmonic waves decreases with the distance of propagation and finally become zero. The generated field could be enhanced several order of magnitude in the gap, so the gap width should be selected accurately. The calculated results of the SAR proved that the best value is the closest to the tissue which causes to the higher temperature generated in it, knowing that the resonance wavelength is varied related to every distance and does not represent the best.

The maximum temperature generated in the tissue under the influence of optical plasmonic bow tie nanoantenna is detected at a distance of 100 nm, which gives a clear indication that the distance from the tissue affects on the distribution field in the tissue and hence on the temperature elevation.

11. Conclusions

Plasmonic Bowtie nanoantennas are designed for single structure at two resonance wavelengths (532, 1064) nm then applied to a proposed skin tissue with a certain environment. The temperature elevation in the tissues is evaluated to estimate its ability to use it as an effective tool for destroying the cancer cells. From the extracted results, it could be concluded:

- The design parameters have a mutual effect on each other at various rates but the length of antennas seems the higher influence.

- Higher near field intensity is detected for single NA at 532 nm than for 1064 nm while the near-field is improved for the resonance wavelength 1064 nm.

- The detected far-field intensity is higher for 532 nm in a single wavelength.
- The distribution of the intensity field in the skin tissues is directly influenced by the resonance wavelength and hence its strength.
- The closest distance of different structures to the treated tissue the better field distribution that raises the temperature.
- The SAR results are higher for short distance (100 nm) according to the field intensity distribution in the tissue.
- The required time period is depending on the SAR taken into account the required temperature for killing tumor cells.
- It is finally concluded that this technique is encouraged to be an effective therapy for destroying the cancer cells.

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