High power titanium Q-switched nano-antennas

Evgeny G. Mironov[1], Ziyuan Li[1] and Haroldo T. Hattori[1]
[1] *School of Engineering and Information Technology, The University of New South Wales, Canberra ACT 2600, Australia*
Evgeny.Mironov@student.adfa.edu.au; Ziyuan.Li@student.adfa.edu.au; H.Hattori@adfa.edu.au.

Abstract: In this paper, we show that titanium based nano-antennas can withstand considerably higher power (18 dB) than their gold counterparts without a significant drop in their electric field enhancement capability.
OCIS codes: 130.0250 (optoelectronics); 240.6680 (surface plasmons); 160.3130 (Integrated optics materials);140.3330 (laser damage).

1. Introduction

Plasmonic nano-antennas can generate highly intense electric fields in small areas [1,2]. These high intense electric fields could be used in a multitude of applications in sensing, imaging and particle detection/manipulation. In general, nano-antennas are excited by large external sources, although their integration with microlasers has recently been proposed [3].

Because of their small volume, nano-antennas cannot withstand high power. When the incident optical radiation is absorbed by the metallic regions of the nano-antenna, fast energy relaxation, thermal diffusion, and energy transfer to the lattice due to electron-phonon coupling [4,5] leads to metal ablation. The power capacity of nano-antennas can be improved by employing pulsed sources which reduces the fluence (energy per area) that reaches the nano-antenna and by an adequate choice of materials. The first approach provides a longer time for cooling and leads to lower fluence per pulse while the second approach requires the use of more resistant materials: the net result is the generation of nano-antennas that can handle highly intense electric fields.

In this article, we compare the performance of pulsed nano-antennas fabricated from different materials, and demonstrate that titanium nano-antennas can withstand considerably more power than their gold counterparts, without a significant reduction in their capacity to enhance the incident electric field.

2. Theoretical analysis

A typical dipole nano-antenna consists of two metallic regions (orange areas) separated by an air gap as shown in Fig. 1 (a fabricated device with 60 nm gap width is shown in the inset). The nano-antenna is placed on top of a quartz substrate and either gold (with a very thin 2 nm titanium adhesion layer) or titanium is used. Gold is commonly utilized in plasmonic devices because of its relatively low losses, but generally doesn't stick well to the surface of quartz, requiring the addition of a thin titanium adhesion layer.

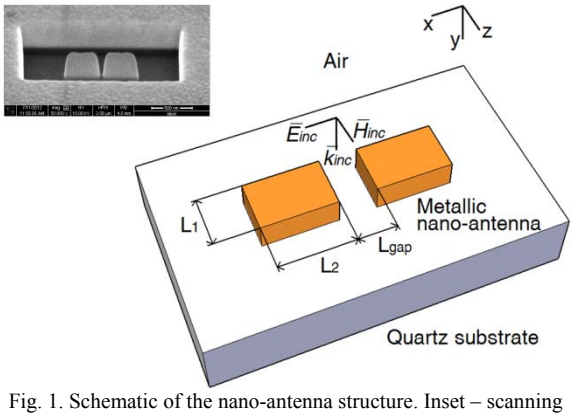

Fig. 1. Schematic of the nano-antenna structure. Inset – scanning electron microscope (SEM) image of device with 60 nm gap width.

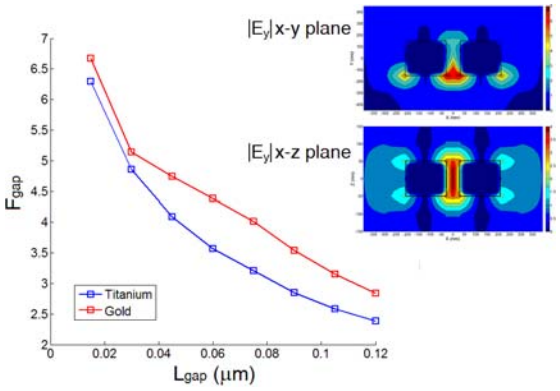

Fig. 2. Electric field enhancement factor F_{gap} as a function of the gap width L_{gap}. Inset – $|\boldsymbol{E}_y|$ for x-y and x-z planes.

The characteristics of the nano-antenna are analyzed by using Finite-Difference Time-Domain (*FDTD*) method [6]. The thickness of the nano-antennas is 300 nm and their length is L_1 = 100 nm. The typical width of the air gap is 60 nm, while the width of the metallic arm is L_2=182.5 nm. A plane wave with a wavelength of 1053 nm and with electric field perpendicular to the gap (E_x) is launched normally to the surface of nano-antenna. Based upon FDTD simulations, it is possible to evaluate electric field enhancement factor of the nano-antenna F_{gap}, which is defined as,

$$F_{gap} = \frac{|\mathbf{E}_{gap,peak}|}{|\mathbf{E}_{inc,peak}|}, \quad (1)$$

where $|\boldsymbol{E}_{gap,\ peak}|$ is the magnitude of the electric field measured in the middle of the dielectric gap region and $|\boldsymbol{E}_{inc,\ peak}|$ is the magnitude of the incident electric field. The magnitude of the electric field can be even higher at the interface between the metallic regions and the air gap; however, the potentially high field enhancement at the edges of the nano-antenna will be lowered during fabrication.

The electric field enhancement factor obtained from *FDTD* simulations is plotted as a function of the gap width in Fig. 2. Based upon this plot, F_{gap} in gold nano-antennas is about 18% higher than in their titanium counterparts, what can be explained by the larger intrinsic losses of titanium. The inset in Fig.2 provides electric field distribution $|\boldsymbol{E}_y|$ inside the gold nano-antenna for a 60 nm gap width. Titanium nano-antenna has a similar $|\boldsymbol{E}_y|$ distribution, but the magnitude of the field is lower because of its higher losses.

Generally, thermal damage of a material is associated with fluence [5]. In the case of a Q-switched laser, the energy of a single pulse $W_{single\text{-}pulse}$ and the fluence $F_{single\text{-}pulse}$ are calculated as

$$W_{single-pulse} = \int_{t_1}^{t_2} P(t)dt = P_{peak}\tau_{eff} \quad (2)$$

$$F_{single-pulse} = W_{single-pulse}\frac{4}{\pi\varphi_{spot}^2}, \quad (3)$$

where $P(t)$ is the envelope of the incident power as a function of time, t_1 and t_2 are arbitrary instants of time when most of the power in the pulse is concentrated ($t_1<t<t_2$) , P_{peak} is the peak power of the incident laser beam, τ_{eff} is the effective duration of the laser pulse and φ_{spot} is the spot-size diameter of the incoming optical beam (which can be expanded or reduced by using lenses). The number of pulses during the period T_{ref} that are generated with repetition rate f_{rep} is $N_{pulse} = T_{ref} f_{rep}$. The effective fluence F_{eff} is given by

$$F_{eff} = N_{pulse}^{p} W_{single-pulse}\frac{4}{\pi\varphi_{spot}^2}. \quad (4)$$

The parameter p varies from 0 to 1 and indicates whether structure has rapidly dissipated heat between two consecutive pulses: $p = 0$ corresponds to the case when the structure has cooled and, thus, the effects of each pulse on nano-antennas will be independent; while, $p = 1$ corresponds to the case of slow thermal effects when cumulative heating of successive pulses take place. *Chang* and co-authors [7] and *Link* and co-authors [8] have shown that the small size of nano-particles resulted in rapid cooling and heating effects. Thus, in our experiment it is assumed that individual pulses damage nano-antennas, because the exposed structures can cool down in the interval between pulses if the exciting laser operates at a low repetition rate.

3. Experimental Results

In our experiments a commercial Q-switched laser that operates at 1053 nm, with single pulse energy of 15 μJ, is used. The duration of each pulse is 10 ns, while the total exposure time is 300 s with a repetition rate of 5 kHz. The experimental setup consists of Q-switched laser, polarizer, divergent lens and variable metallic-film neutral density filter as presented in Fig. 3.

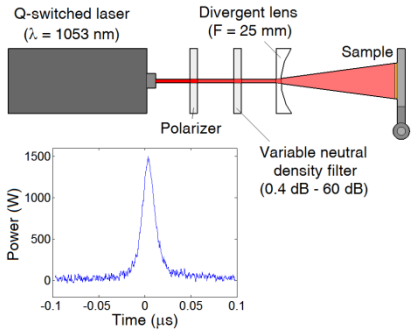

Fig. 3 – Experimental setup. Inset – single pulse profile

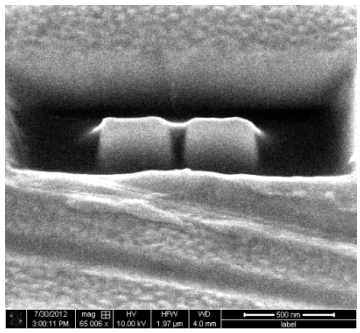

Fig. 4 – Damaged gold nano-antenna

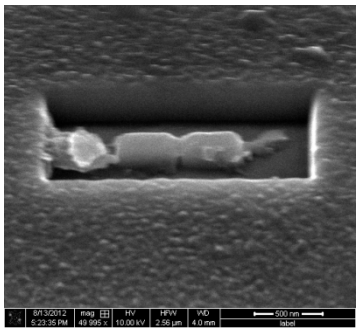

Fig. 5 – Damaged titanium nano-antenna

Both metals are deposited by using an electron beam evaporator (gold nano-antenna also has a 2 nm thick adhesion titanium layer). The structures are then patterned by using a FEI Helios NanoLab 600 dual-beam FIB system. The experiments are focused on samples with 60 nm gap width. After each experiment at a given

fluence the SEM image is taken to estimate the damage to the nano-antenna (Fig. 4). Experiments showed that for gold nano-antenna single pulse damage fluence was $F_{single\text{-}pulse} = 0.059$ J/m^2, while the total exposure fluence ($T_{ref} = 300$ s and $f_{rep} = 5$ kHz) was $F_{ex} = 88.5$ kJ/m^2. The main damage occurred inside the gap (where the field enhancement reaches the highest value). A similar experiment was conducted for titanium nano-antenna (Fig. 5) and the damage single pulse fluence was estimated to be 4.35 J/m^2 and the total exposure fluence was 6525 kJ/m^2.

By using a titanium nano-antenna the damage fluence has increased by a factor of 74, though the electric field enhancement has dropped by only 19%. In other words, titanium based nano-devices could handle and create about 7 times higher electric fields than their gold counterparts [9].

The better performance of titanium nano-antennas could be attributed to: higher melting temperature (1668^{o}C against 1064^{o}C), increased mechanical strength, and larger skin depth. Moreover, due to a larger skin depth, the power is more uniformly distributed inside the titanium nano-antenna than in the gold one. Titanium is also known to be a resistant material that can withstand moderately high temperatures and is widely used in marine and aerospace applications.

4. Conclusion

In this short paper, we compared the performance of gold and titanium based plasmonic nano-antennas when they are excited by external large spot-size diameter Q-switched laser sources. In the first part of the experiment, it was observed that, if the spot-size diameter of the incoming radiation, the fluence of the optical beam reaching the nano-antenna is reduced and avoids its destruction. In the second part of the experiment, we observed that titanium nano-antennas can withstand considerably higher fluence (18 dB) than their gold counterparts: these titanium based nano-antennas could lead to applications such as the development of more sensitive sensors with larger signal-to-noise ratio, excite nonlinear effects more easily and produce stronger forces that could attract and detect larger nano-particles. FDTD simulations have also indicated that the field enhancement factor produced by titanium nano-antennas is not much lower than their gold counterparts given the small areas of the metallic regions, although it is true that the losses could become important in an array of such nano-antennas or in meta-materials [10].

5. References

[1] N. Yu, E. Cubukcu, L. Diehl, D. Bour, S. Corzine, J. Zhu, G. Höfler, K. B. Crozier, and F. Capasso, "Bowtie plasmonic quantum cascade laser antenna," *Opt. Exp.*, vol. 15, pp. 13272-13281, 2007.

[2] P. Bharadwaj, B. Deutsch, and L. Novotny, "Optical Antennas," *Advances in Opt. and Phot.* , vol. 1, pp. 438-483, 2009.

[3] H. T. Hattori, Z. Li, D. Liu, I. D. Rukhlenko, and M. Premaratne, "Coupling of light from microdisk lasers into plasmonic nano-antennas," *Opt. Exp.*, vol. 17, pp. 20878-20884, 2009.

[4] M. E. Fermann, A. Galvanauskas, G. Sucha, *Ultrafast Lasers: Technology and Applications,* New York : Marcel Dekker2003, pp. 359-394.

[5] H. Sobral and M. Villagrán-Muniz, "Energy balance in laser ablation of metal targets," *J. of Appl. Phys*., vol. 98, 083305 1-5-, 2005.

[6] H. T. Hattori "Analysis of optically pumped equilateral triangular microlasers with three mode-selective trenches," Applied Optics, 47, pp. 2178-2185, 20 April 2008.

[7] S.S. Chang, C.W. Shih, C. D. Chen, W.C. Lai, and C.R.C. Wang, "The shape transition of gold nanorods," *Langmuir*, vol. 15, pp. 701-709, 1999.

[8] S. Link, C. Burda, B. Nikoobakht, M.A. El-Sayed, "How long does it take to melt a gold nanorod? A femtosecond pump-probe absorption spectroscopy study," *Chem. Phys. Lett.,* vol. 315, pp. 12-18, 1999.

[9] E.G. Mironov, Z. Li, H. T. Hattori, K. Vora, H. H. Tan, and C. Jagadish, "Titanium nano-antenna for high-power pulsed operation," submitted to Journal of Lightwave Technology.

[10] B. Lahiri, R. Dylewicz, R. M. De La Rue, and N. P. Johnson, "Impact of titanium adhesion layers on the response of metallic split-ring resonators (SRRs), " Opt. Express, vol. 18, 11202-11208, 2010.