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High Quality Factor Plasmonic Laser Based on Two Cavity Design

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Abstract— Plasmonic nano cavities is type of nano-cavities that appeared in the last decades. Plasmonic cavities based on surface plasmon polariton that using metal to confine light below its diffraction limit. Diffraction limit is the most important problem in the semiconductor cavities. But the problem of using metals to confinement the light is high losses that lead to reduce quality factor so that dielectric sandwich dielectric layer is used to minimize losses. Using two cavity design also another way to increase quality factor based on coupling between two cavities. This design gives quality factor equal to 500, mode volume $0.095(\lambda/2)^3$ and Purcell Factor 680. This design that uses two rectangular cavities provided very small mode volume without any diffraction in the light.

Index Terms— Surface Plasmon Polaritons (SPP), Plasmonic, Nano-cavity, Quality factor, Diffraction limit, Plasmonic nano cavities, Plasmonic laser.

1 Introduction

THE Plasmonic laser is a type of laser appeared in the last decade, plasmonic laser is the laser that has a very compact size without diffraction limit. Diffraction limit that avoids light to concentrate below its wavelength scale. This type of laser will be based on surface Plasmon Polaritons (SPP) technique using metal to confine light. For any system using light as information carrier, length of the cavity must be (n λ/2), where n is integer number and λ is wavelength of light, but using plasmonic laser will break this rule.

Most optical micro and Nano-cavities designed so far use the dielectric materials. From there, the size of the cavity is limited by the diffraction limit of light, while the Plasmonic cavities that have ability to further of the mode volume (Vm) reduction to sub wavelength scale, but take part a somewhat high quality factor (Q) owing to Surface Plasmon Polaritons (SPPs) effect, which suggested as a stand by [1]. Nano lasers are favorable coherent light sources for densely photonic integrated circuits due to their fast modulation, extremely low power consumption and very small size [1, 2]. In particular, surface Plasmon Polaritons lasers are open new fields of research because they can confine light below its diffraction limit because it is used metal to confine light. Nano laser based on dielectric cavities, like nanowires, metal-cladding cavities and photonic crystals, which have sizes physically limited by the wavelength limit. But, losses caused by metallic absorption and cavity radiation are prevented by SPP lasing at room temperature. The reduction of these losses would allow new practical applications [2].

Plasmonic lasers realize confinement and feedback optical signal by employing SPPs, quasi-particles that result from interaction between photons and free electrons at interface of metal and dielectric that had been amplified by using the appropriate optical gain medium.

Particularly, Plasmonic laser work near the surface Plasmon frequency amplified light that coupled with oscillated electrons that inserted additional moment to light, where the electromagnetic field propagates an energy that equal to the polarization of electrons, that increases confinement and loss. The plasmonic lasers expectancies are ultrafast amplifiers, owing to it's confined an optical and the parallel high Purcell effect [3, 4].

Plasmon laser has a minimum physical size of only a some nanometers, surrounded just by a metal's homogeneous and non-local length scale (1 nm) contrast to this regime [3,4]. The conventional semiconductor laser cavity mirrors are coated with a layer of metal with a process called slivering to increase the reflectivity and confinement of laser beam in the cavity. This process is not needed in the plasmonic laser which has metallic mirror that acts as good reflectors.

A surface Plasmon laser which can concentrate light to dimension smaller than diffraction limit can effectively replace conventional laser. The main problem that need to be solved for plasmonic cavities is high loss which is induce by metal and which leads to reduce the quality factor. One of the best solutions to this problem is by using the gain medium to compensate the losses that happen during the round trip of light and amplify it. The gain dielectric medium will surround the metal nanostructure to reduce losses that limit propagation of SPP on metal surface.

Generally, lasers with electrical injection will be more useful in practical applications than those with optical pumping [2]. Electrical injection is one of the greatest advantages of semiconductor lasers over most of other lasers such as solid-state lasers, where only optical pumping is possible. Currently, the metal cavity can serve as an electrode and so that no dramatic increase in the complexity of fabrication is required, as in the case of a photonic crystal laser [5].

Although plasmonic effects have been known for more than a century, the history of Plasmon based applications began in early 1970, when Martin Fleischman and others began to study how light scatters from molecules stuck to silver surface. Richard Van Duyn, which discovered this scattering to be enhanced seemingly unbelievable six orders of magnitude. In 2003, Bergman and Stockman suggested that by using laser with localized surface Plasmons [6] , a coherent light field can be generated cohesive light field immediately at the Nano-scale, but the first decision of using laser action in metallic Nanocavities occurred in 2007, where encapsulated around semiconductor stake in a dielectric and then the gold was electrically pumped [7].

The first structure of laser was proposed in 2007, by using a gain medium made of semiconductor core and a wave confined by metal shell mechanism to minimize the sizes of semiconductor lasers with extra than 1- dimension exceed that is reasonable with cavities that use pure dielectric materials[6].

In 2008, Mariano A. Zimmler and workers proposed direct evidence of the transition from amplified spontaneous emission to laser action in optically pumped zinc oxide ZnO nanowires, at room temperature [8].

In 2009, Hill and co-workers defined Metal-Insulator-Metal (MIM) cavities, which contain narrow slit between two metal walls sandwiching a gain medium layer [9]. This is called waveguide-cavity that supports one dimension confined plasmonic between the walls of metal by providing a waveguide mode confinement, which interferes with gain medium that made from (InGaAs). In same year, Oulton, et al. reported a hybrid nanowire Metal1-2Insalator5-Simiconductor5 (1MIS2) Plasmon laser [9]. This MIS hybrid design achieved high opti6cal confineme3nt in the region of separated gap (which had thick of only a few nanometers) in each dimension. Where the two ends of the metallic Nano-wire act as mirrors to contain a Fabry-Perot cavity. In other research in 2009, Noginov and workers teem suggested using a localized surface Plasmon laser consist of spherical gold particle with a dielectric clad has a volume of only 44 nm in diameter [10].

In 2010, Ma et al. suggested a semiconductor plasmon laser that works at room temperature [11]. In this design, the radiation loss was mitigated by adopting total internal reflection of SPPs, while using the hybrid MetalInsulator-Semiconductor5 with a squares Nano-cavity structure was designed. Such laser structure provide robust confinement and at same time low5 met2al and radiation loss, this enabled its operation at room temperature. It has a very small cavity size as compared with other studied devices operating at room temperatures.

Nano-lasers have been provide many types of metallic cavity worldwide. Most of these types were recognized by using an optical pumping. In 2010, Nezhad et al. studied a circular metallic-dielectric Nano cavity laser. With an optimized thickness of the dielectric layer, they had been used TE mode lasing using optical pulse pumping at room temperature. Later in 2011, Lee et al. enhanced this construction with electrical injection. This introduced design of laser configuration was to increase the quality of the cavity.

Finally, Yu et al. offer laser with a metal–semiconductor–metal sandwich structure called Nano patch laser (2012). In same year, Qing Wang, [1] investigated the use of two coupled identical disks that forming a (hybrid photonic/ plasmonic molecule). Every one of these disks represents a metal-dielectric structure that provides a hybrid plasmonic-photonic Whispering-Gallery modes. This laser has high quality factor but has low Purcell factor because of big volume.

In 2014, Themistoklis P. H. Sidiropoulos [12] suggested using the supervision of pulses5 that less than2 (8005) by using a hybrid-P5lasmonic Zinc Oxide (ZnO) nanowire lasers. These ZnO excitons work at room temperature, lies near the SP frequency for plasmonic lasers that are based on silver that leads to accelerated spontaneous recombination of gain switching and gain recovery as compared with classical nanowire laser that use Zinc Oxide.

All the above method suggested plasmonic laser but all of them has low quality factor and high metallic losses.most of the above researches are using the optical injection and they only 1-D confined laser. In this paper we suggested small volume, high quality factor with two cavity plasmonic laser based on sandwich dielectric layer.

2 Proposed system:

The penetration to metal increases significantly at high frequencies in near infrared and visible part of the spectrum, and the electromagnetic wave interacts with the metal surface free electrons (Plasmon) at this region. Surface Plasmon polaritons (SPP) and localized surface Plasmon resonance (LSPR) are two controlling methods for this interaction which is the basic idea of the Plasmonic laser concept. Surface Plasmons can be defined as a wave propagated along the surface of the conductor. The most important reason for interest with surface Plasmon was its ability to structure the metal in Nano scale. This can be lead to miniaturizing the photonic circuits with length scales much smaller than those currently accomplished [13]. These circuits will first convert light into Surface Plasmons that would be then propagated and processed by logic components, before converting back into light.

Most of conventional configurations of laser cavities are based on dielectric materials which disable confining light below its diffraction limit. Using metals can solve this problem to form laser resonators. Using metal cavities has two forms, either strong, compact mirrors, that's able to confine light below its diffraction limit, or the light may interact strongly with the free electrons in the metal, being guided at the interface between a metal) and a dielectric material. This technique enables reducing the size of laser to few nanometer scale, also can use as integrated circuits [14, 15].

However, using metal to reduce the size of the laser and provides heat sink, but it has losses higher than the losses at dielectric cavities. The energy dissipated due to collision electrons, so that SPPs can travel only short distances. This lead to the small value of a lifetime for conduction electrons and then few store energy and less quality factor which represents an important factor in laser cavities. Using gain medium losses in metal can compensate this loss and improve the quality factor of plasmonic lasers. Where the time constant for spontaneous emission, τ, is the average time taken by an electron to decay. The extremely small optical modes associated with metallic nanostructures drastically modify the rate of spontaneous emission, which in turn modifies the laser process. It is critical to account for this modification as it can influence a laser's threshold by orders of magnitude. Metallic Nanostructures generally see enhancement for just a few of their optical modes. While the most confined modes will exhibit fast emission coupling rates, less well confined modes have relatively slower coupling rates. This leads to preferential coupling to the most confined modes.

Although there are many challenges, the construction of Nano-laser is similar to that of conventional laser. SP is generated at metal interface and amplified by a dielectric structure which represents a gain medium The gain medium amplifies the SP by stimulated emission, while feedback mechanism allow SP to resonate. By varying the frequencies of the incident light, different surface charge density distributions can be generated for long-range SPPs propagation.

The part of the structure that will be changed is the cavity of the laser. The cavity must designed to achieve a high quality factor. But using metal to confine light below the diffraction limit $(\lambda/2n)^3$ will increase losses and then reduce the quality factor of the laser, so that noble metals (gold, silver) are used because noble metals has low loss. High gain material is used to compensate losses in the cavity. At shorter wavelength this situation is different owing to large metal losses at near infrared and visible range [6].

3 Design of Resonance Cavity

There is many types of laser cavities but all types must be made to amplify the light inside the cavity and has good reflectivity. The light enters the plasmonic cavity will amplified by SPP and stimulate to emit laser. The distance between cavities and shape of the mirrors are important factors for laser cavities [16]. There are various types of stable two mirror of the laser cavity design. These types of resonators differ in their focal lengths of the mirrors (governed by the mirror's radius of curvature) and in their distance between the mirrors (cavity length). Some beams have different shapes within the cavity and are thus chosen for different purposes. Assume R1 and R2 are the radiuses of the mirrors and l is the distance between cavities. According to these factors the stability condition for laser cavities can be estimated. Introducing two variables $g1$ and $g2$, where $g1 = 1-(l/R1)$ And $g2 = 1-(1/R2)$. Then the laser cavity will be stable if $0 \le g1g2 \le 1$.

If the value is out of this range this mean that laser cavity is not stable and one of the cavity parameter must change to match with the stability condition. This represent the main condition for cavity design but there is other parameters that can affect the laser cavity such as material choice. Choosing proper metal as mirrors and proper active material supported the thermal and gain stability. If the cavity is unstable, the beam size will grow without limit, eventually growing larger than the size of the cavity mirrors and being lost.

The distance between mirrors is practically the optical path length. This distance is not empty but filled by the active gain medium, where the proper gain is added to the laser beam. The shape of laser beam depends on the distance between cavities, type of mirrors and number of the mirrors used in the laser cavity. In the suggested structures two coupled flat cavities design is used of these cavities was chosen to design laser cavity. The mirrors is made of silver and active material made of direct band gap semiconductor such indium phosphate material. There are two types of metallic cavities MDM (metal dielectric metal) and MIS (metal insulator semiconductor) [9].

The use of the MIS type provided two advantages over the other types. First, using dielectric layer will reduce absorption caused by using metal and then the losses are reduced by using metal. Sometimes this dielectric layer is not only used to reduce loss, but also is used as gain material or secondary gain material. Second, the use of semiconductor material such as GaAs which act as active material and gain material provides good compensator for the laser beam.

Many studies suggested the design of laser with Nano-scaling taking into their account the confinement factor and how to confine light by using metal. But one of the most important factors in the laser work is quality factor. The quality factor (Q) is defined as the ratio of energy stored in the cavity to energy dissipated per oscillation cycle. Quality factor value is inversely proportional to losses. But how can get good quality factor with high losses of metal cavity, dielectric cavities have high quality factor but cannot confine light below the diffraction limit and nano-cavities has good confinement but low quality factor. The problem of nano cavities can be solved by adding dielectric layer in between active material and metal.

To implement a “plasmonic” cavity according to the above principle, a resonator using dielectric layer was proposed. The dielectric layer is sandwiched in between metal plate and semiconductor layer as Fig. (1). The strong confinement of optical mode is the dielectric layer inserted between metal and semiconductor. Metallic-dielectric structures guides SPPs but they have drawback of high attenuation. Using optical gain to compensate for the losses of materials allows SPPs to propagate for longer distances and change the metal confinement trade-off [28].

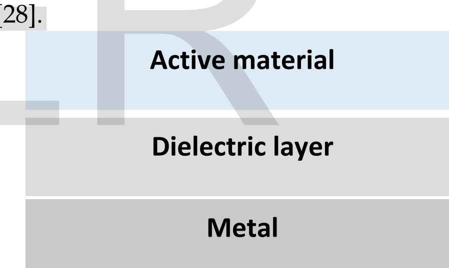

Fig. 1. Metal dielectric semiconductor arrangement.

Using hetero-structure such as InP in the middle of structure compensated the losses of metal through the optical gain in this layer. By using the electrical injection pump to the entire structure can achieve the lasing or amplification of optical though most demonstrated Nano-lasers with electrical injection have a cavity with circular cross-section, the size of the cavity could be reduced in each direction independently. Here, two rectangular cavity Nano-lasers will discuss and realize at room temperature CW operation of sub wavelength metallic cavity lasers under electrical injection. Several fabrication issues for the electrically driven metallic cavity Nano-lasers and its possible integration with other photonic components will be discussed as well.

Another important for laser is Purcell factor, Purcell factor means enhancement of spontaneous emission, it is given by (1)

$$F = \left(\frac{3}{4\pi^2}\right)\left(\frac{Q}{V_{mode}}\right)\left(\frac{\lambda}{n}\right)^3 \quad (1)$$

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Where Q is the cavity quality factor, Vmode is the mode volume, λ is the resonance wavelength and n is the refractive index of the medium. Equation 2 explain the rate at which the weakened coupled systems could interchange energy with an optical mode

$$V_{mode} = \frac{\int P(r) d^3 r}{P_{max}} \quad (2)$$

Where $P(r)$ is the electromagnetic energy density of the mode, and Pmax is the peak value of $P(r)$. Purcell noted that light-matter interaction rates can be enhanced by reducing the optical mode volume and increasing the Quality factor of a resonant cavity.

The algorithm of plasmonic laser work illustrated in fig. 2. The algorithm describe the work of plasmonic laser. When the SPP generated in the interface of metal dielectric layer this will act as additional pump that stimulate the active layer to emit laser.

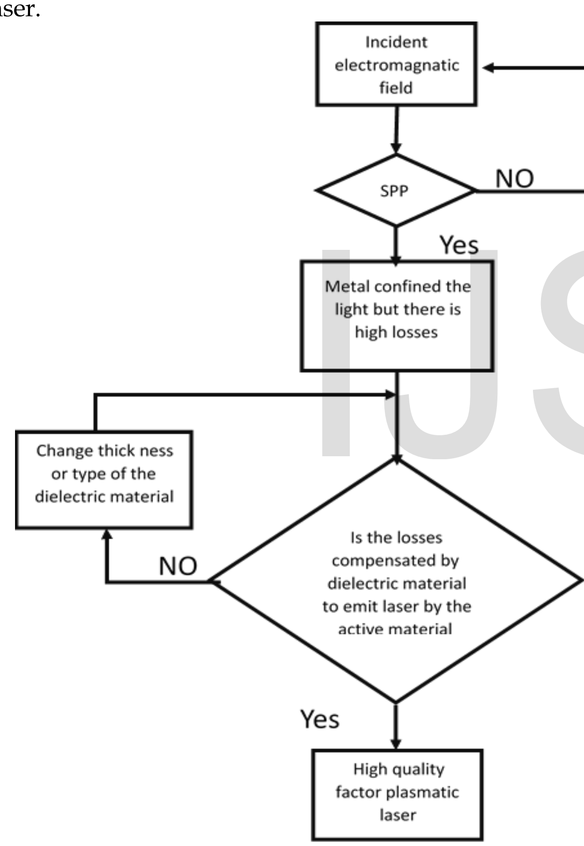

Fig. 2. Algorithm of plasmonic laser work.

This design suggest using two cavities to increase quality factor by make coupling between two cavities. This design represent first step to laser array. The cavity design shown in Fig. 3 consist of two rectangular cavities each cavity has dimensions (205*250) nm. The metal used in this design is silver (Ag), dielectric layer is Silicon dioxide (SiO2) with refractive index nSiO2=1.5, active medium Indium Phosphide (InP) with refractive index nInP=3.4 and filled by air. Dimensions of the cavity are *lc* equal to (1500 nm), w equal to (500 nm), d=100 nm, h= 700 nm, distance between center of cavities 500 nm.

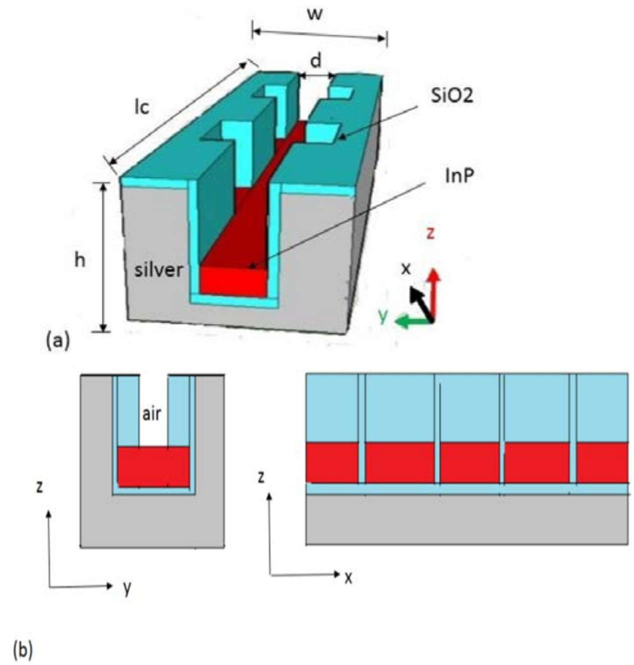

Fig. 3. a) Two cavity design b) Cross section of front and side of the cavity.

Multifrontal Massively Parallel Sparse Direct solver (MUMPS) numerical in COMSOL Multiphasic 4.4 2013 software is used. The work is implanted in frequency domain. The calculation of quality factor is done by using integral to cavity.

4 EXPERIMENT AND RESULTS

The two cavity design has different width was suggested and study its effect on quality factor, field confinement and enhancement and study its frequency region. The coupling between plasmonic cavities provides new modes of operation. The plasmonic Nano cavity consists of two identical rectangular cavities. Two of these rectangular cavities are sandwiched like geometry composed of the cavity filled with top air and InP (active material), SiO2 and the bottom is the surface of a sliver. Figure 4 shows the electric field distributed in the two cavities, while Fig. 5, a show the current density in the cavity and Fig. 5, b show the losses distribution in the cavity. Notice that losses distributed in the metal of the cavity. The losses in the design were concentrated near the surface of metal as shown in Fig. 5, b. These losses are due to skin effect on metal, and the depth of penetration of losses is dependent mainly on the type of metal and frequency. When frequency becomes higher, the skin depth becomes lower because the current stay on the surface of metal and there is no ohm loss. Sometimes energy appears in one cavity and dissipates in the second cavity. This phenomenon is due to the wavelength of the wave used in the experiment. When the top of cavity concentrates in one cavity its energy become high but some of the energy dissipated in the metal.

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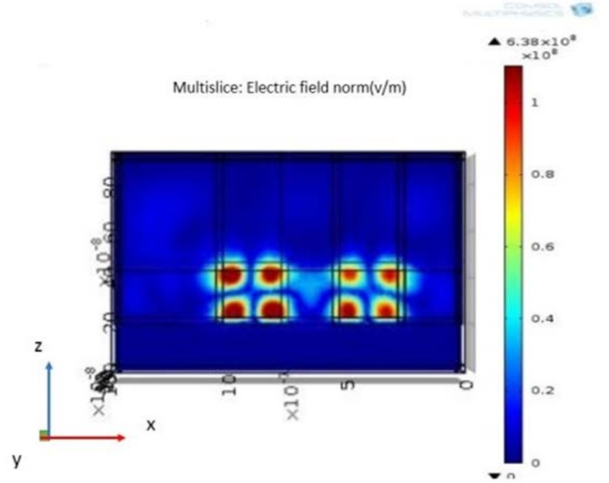

Fig. 4. Electric field distribution in the cavity.

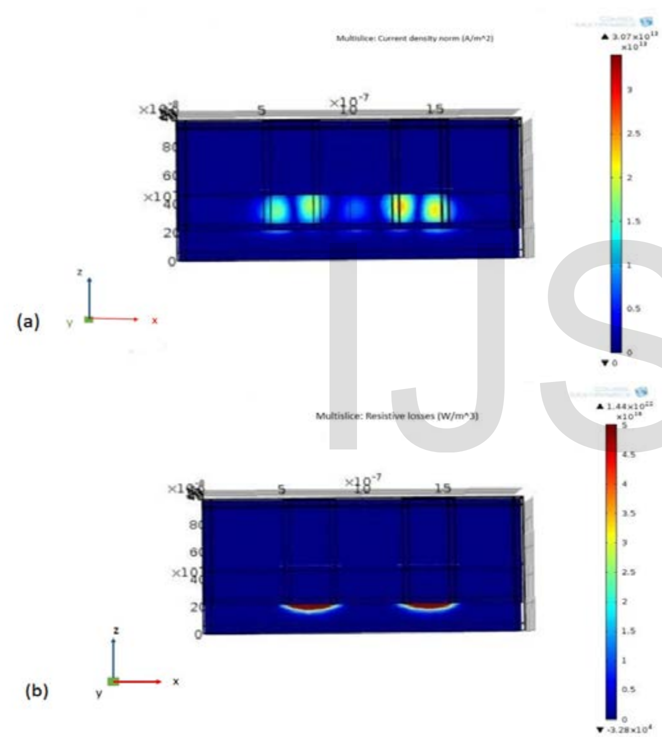

Fig. 5. a) Current density distribution. b) Losses distribution.

There are two types of cavity modes that could be excited in the suggested structure; "transverse electric (TE)" and "transverse magnetic (TM)" modes. For the hybrid photonic-plasmonic, most fraction of energy of TM mode was confined in the dielectric layer that cover the surface of metal. But most fraction of energy for TE mode, was stored in the semiconductor layer. In practice, only TM-mode was discussed in this thesis because the TM mode is more favorable than TE-mode for realizing the sub wavelength application.

Figure 6 abbreviated the dissipation of energy in the structure design. And this phenomenon also dependent on distance between cavities when the distance between cavities increased the dissipated power increased because the plasmonic coupling between two cavities be weak. In this design if the distance between centers of the two cavities increases, the resonance wavelength will shift to 600 nm. The distance between cavities not only affects the decay of the wave, but also affects the quality factor values as shown in fig. 7. This effect attributed to distance between resonated mirrors in the cavity. Quality factor is strongly affected by the shape and volume of the cavity. In this design, if the cavity becomes smaller the quality factor degrade because the total internal reflection is very weak.

When the distance between two cavities increased from (250) to (500) nm the resonant wavelength increased owing to an increasing coupling strength weakened between cavities. As the distance increased more from 500 nm to 1000 nm, and the quality factor value decreases from 500 to 400. When the distance between the two metal surfaces becomes smaller than the inverse of the exponential decay constant of the surface plasmon polaritons modes of the isolated mirrors, the two plasmonic modes hybridize and form a gap mode plasmon. The electric field intensity could be significantly larger as the gap thickness is much less than the normal decay constant.

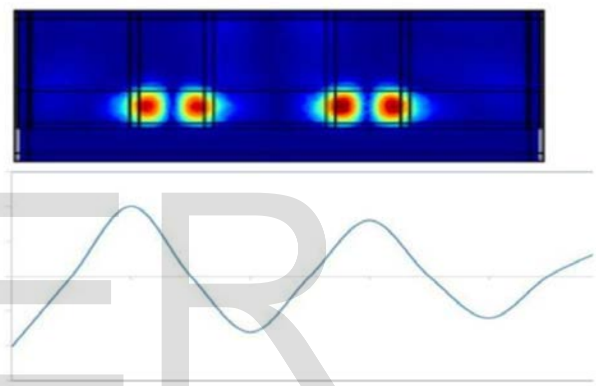

Fig. 6. Decay in the cavity.

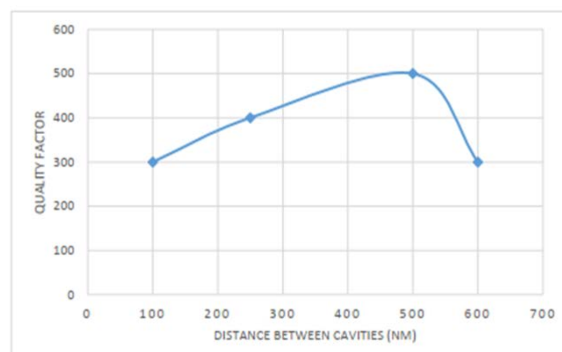

Fig. 7. Quality factor change with different distance between cavities.

Quality factor value also dependent on the thickness of dielectric layer that sandwiched between active layer and metal as shown in table 1. From table 1 notice that the raise in quality factor value by increasing thickness of the dielectric layer is limited that's due to light deviation by the dielectric layer. Changing of the thickness of the dielectric layer not only affected on the value of the quality factor it cause shift in the resonance frequency as shown on fig. 8. The best thickness for dielectric layer in resonance frequency equal to 550 nm as shown in fig. 9.

This cavity design gives quality factor equal to 500 at reso-

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nance wavelength 550 nm, mode volume is $0.09(\lambda/2)^2$ and Purcell factor 413. If compared this cavity design to another study that proposed using two disks; each one of these disks contains a metal-dielectric configuration that supports Plasmonic-photonic hybrid Whispering-Gallery modes.

TABLE 1
UNITS FOR MAGENTIC PROPERTIES

Wavelength(nm)	Q at t_{low}=25nm	Q at t_{low}=30nm	Q at t_{low}=35nm	Q at t_{low}=40nm
3000	10	24	20	20
1500	60	63	69	70
1200	90	97	97	95
1000	155	161	170	176
860	67	66	80	89
750	121	145	211	316
667	100	129	135	161
600	285	314	314	277
545	400	500	178	268
500	255	162	181	261
450	139	209	269	335
400	100	150	324	249

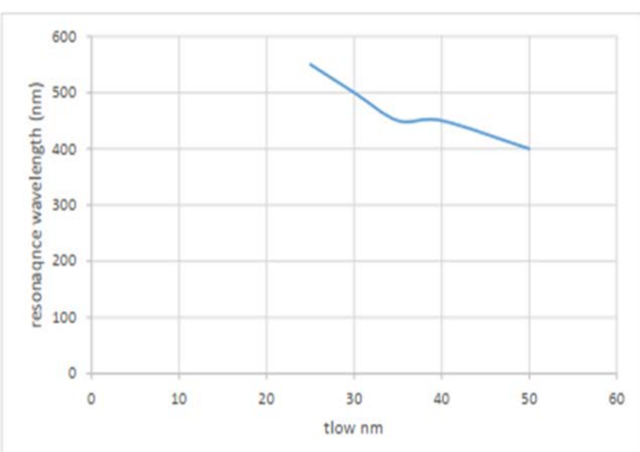

Fig. 8. Resonance wave length versus thickness of dielectric layer.

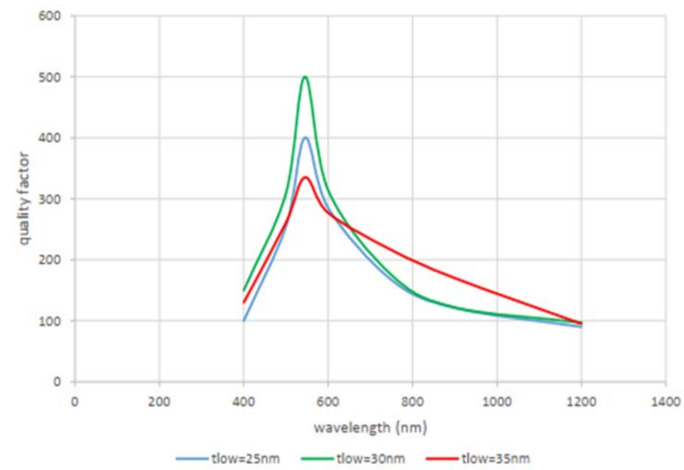

Fig. 9. Quality factor versus wavelength for different width of dielectric layer (using silver).

The cavity design that has two cylindrical cavities has big volume if compared with design of two rectangular cavities. So that although the structure of cylindrical cavities has larger quality factor but it has lass Purcell factor due to large mode volume and then small quality factor to mode volume ratio.

5 CONCLUSION

Using two cavities with same dimension of single cavity increase quality factor because of the coupling effect between two cavities, and the distance between these two cavities. Distance between cavities also affected the energy of the cavities as shown in the fig. 9, where sometimes on cavity work on and second off because different of wave length and concentration top of wave in the cavity. The energy will concentrate in the dielectric layer because of its polarization property which guide the electric field.

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