Enhancement of emission and directionality of Light Emitting Diode using Surface Plasmon Resonance

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1. INTRODUCTION

The Surface plasmons which is a collective oscillation of free electron at metal dielectric interface has been used in many optical devices (Chen et al., 2006), and the idea of SP enhanced light emission was previously described (Vuckovic et al., 2000, Gontijo et al., 1999, Iwase et al., 2008).

The use of plasmonic circuits needs methods to generate directional plasmons and to reflect, diffract or focus the energy. These plasmonic controls are now becoming possible (Ditlbacher et al., 2002).

Directional surface plasmons can be created by laser illumination of a silver wire on a silver film. The plasmons are seen to be strongly directional and can be migrated to distances greater than 10µm. The next step for plasmon circuits is the fabrication of optical elements on a metal surface to manipulate the plasmons.
This can now be capable for using dielectric or metallic structures on a metal film (Devaux et al., 2003, Krenn et al., 2003). Studying the passive control of light by using surface plasmons dates back to the late 1990s. According to the authors best knowledge a significant work by Ebbesen et al. can be selected as a good starting point in this area (Ebbesen et al., 1998).

Ebbesen et al. showed that the transmission is related to the coupling of photons in the surface plasmons. The coupling is possible due to the metal film being periodically patterned with the cylindrical apertures. Kim et al. (Kim et al., 1999) found some unanticipated and talented results in this field. According to their results the light was shone on a two-dimensional array of cylindrical holes through a 0.2 μm silver film. It was found that zero-order light with a wavelength of up to ten times the diameter of the holes can be transmitted. Moreover, sharp peaks in transmission were observed, with a transmission efficiency (normalized on the area of the holes) often exceeding unity, this value is orders of magnitude greater than what would be expected from standard aperture theory.

Later Thio et al. (Thio et al., 1999) using the Ebbesen et al. (Ebbesen et al., 1998) input took a closer look at this effect.

It can be noted that Schröter et al. (Schröter and Heitmann, 1998) in their valuable work dealt with transmission through metallic gratings with arrays of holes/apertures Kim et al. (Kim et al., 1999) and later Lezec et al. (Lezec et al., 2002) investigated the transmission through a single aperture. They individually found that by means of using a textured surface around the aperture, in this case, concentric circular gratings, they could control the divergence of the emerging beam. Using such a sub-wavelength aperture would normally result, in light being diffracted over a wide range of angles. According to Kim et al. (Kim et al., 1999) and Lezec et al. (Lezec et al., 2002) results the divergence was shown to be ±3°. Interestingly, the angles of emission could be controlled spatially by altering the period of the grating. In the coupling process, the energy of the light emitter can be transferred into SP modes and then radiates such that the effective emission efficiency can be enhanced. Also the SP modes can absorb incident light and transfers the energy into a light absorber thus its effective absorption can be enhanced (Yeh et al., 2008).

This investigation is theoretically designed to intensely focus on the effect of the geometry of the hole array, as well as the importance of the diameter of the hole itself. The wavelength maxima were calculated through understanding the coupling that occurs between the incident light and the surface plasmons.

Additionally, the aim of this work is calculating the amount of coupling between light emitted by LED and surface plasmons. Similarly, this investigation analyze the coupling equations dependence on wavelength and grating period which they affect the direction of the emitted beam.

2. MATERIALS AND METHODS

For momentum conservation, and thus for coupling to occur, this condition must be valid:

\[ k_{sp} = k_{ph} + iG_x + jG_y \]

Where \( k_{sp} \) is the wave-vector of the surface plasmons, \( k_{ph} \) is the wave-vector of the incident light. \( G_x \) and \( G_y \) are the k-space vectors of the periodic grating, where \( i \) and \( j \) are simply integers. This can be rearranged to show the resonance wavelength of the incident light at differing values of lattice integers \( i \) and \( j \). The wavelength values obtained from these equations matched well with their experimental results.

One of the powerful methods for developing efficient solid-state light emitters is coupling. To design and fabricate even more efficient SP-enhanced optical devices for a wider spectral range, tuning of the SP mode is very important to achieve matching condition of the energy coupling. Meanwhile the wave vector of the photon in free space is not equal to wave vector of the surface plasmons. Thus, surface plasmons created at the interface of dielectric medium and metal must be coupled with photons in vacuum by a device such as grating as shown in Fig. 1.
And the mathematical relation is (Linqing and Yanwu, 2014):

\[ k_{sp} = k_0 n \sin \theta_R + \frac{2\pi}{\lambda} = k_0 \sqrt{\frac{\varepsilon_m n^2}{\varepsilon_m + n^2}} \]  

(1)

where \( K_{sp} \), \( K_{ph} \) are wave vector for surface plasmons and photon in free space respectively, \( n \) is refractive index of the dielectric material, \( \theta_R \) is a resonance angle and \( \varepsilon_m \) is the dielectric constant of the metal. For two dimensions grating one can compute the overlapping the area of two circles for \( k \)-vector of the photon in free space and surface plasmons mathematically as follows:

For two circles with radius \( k_{ph} = r \) and \( k_{sp} = R \), two circles may cross in two imaginary points, a single degenerate point, or two separate points as shown in Fig.2. The intersections of two circles determine a line known as the radical line. If three circles mutually intersect in a single point, their point of intersection is the intersection of their pairwise radical lines, known as the radical center.

Let two circles of radii \( K_{sp} \) and \( K_{ph} \) and centered at \((0,0)\) and \((d,0)\) intersect in a region shaped like an asymmetric lens. The equations of the two circles are:

\[ x^2 + y^2 = k_{sp}^2 \]  

(2)

\[ (d - x)^2 + y^2 = k_{ph}^2 \]  

(3)

And the mathematical relation is [16]

Combining (1) and (2) gives

\[ (k_g - x) + (k_{sp}^2 - x^2) = k_{ph}^2 \]  

(4)

Multiplying through and rearranging gives:

\[ k_g^2 - 2xk_g + x^2 - x^2 = k_{ph}^2 - k_{sp}^2 \]  

(5)

Solving for \( x \) results in:

\[ x = \frac{k_g^2 - k_{ph}^2 + k_{sp}^2}{2k_g} \]  

(6)

The chord connecting the cusps of the lens therefore has half-length \( y \) given by plugging \( x \) back in to obtain:

\[ y^2 = k_{sp}^2 - x^2 = k_{sp}^2 - \left( \frac{k_g^2 - k_{ph}^2 + k_{sp}^2}{2k_g} \right)^2 \]  

(7)

Solving for \( y \) and plugging back in to give the entire chord length \( a = 2y \) then gives:

\[ a = \frac{1}{k_g} \sqrt{4k_g^2k_{sp}^2 - (k_g^2 - k_{ph}^2 + k_{sp}^2)^2} \]  

(8)
To find the area of the asymmetric "lens" in which the circles intersect, simply use the formula for the circular segment of radius $k_{sp}'$ and triangular height $d'$

$$A(k_{sp}', k_{ph}) = k_{sp}'^2 \cos^{-1} \left( \frac{k_{ph}}{k_{sp}'} \right) -$$

$$k_{ph} \sqrt{k_{sp}'^2 - k_{ph}^2}$$

(10)

twice, one for each half of the "lens." Noting that the heights of the two segment triangles are:

$$d_1 = x = \frac{k_{ph}^2 + k_{sp}^2}{2k_{ph}}$$

(11)

$$d_2 = k_{ph} - x = \frac{k_{ph}^2 - k_{sp}^2}{2k_{ph}}$$

(12)

The result is:

$$A = A(k_{sp}, d_1) + A(k_{ph}, d_2)$$

(13)

The result is:

$$\text{Area} = (k_{ph}^2 \cos^{-1} \left( \frac{k_{ph}^2 + k_{sp}^2 - k_{sp}^2}{2k_{ph}k_{sp}} \right) +$$

$$k_{sp}^2 \cos^{-1} \left( \frac{k_{ph}^2 + k_{sp}^2 - k_{ph}^2}{2k_{ph}k_{sp}} \right) -$$

$$\frac{1}{2} \left( (k_{ph}^2 + k_{sp}^2)(k_{ph} + k_{sp}) - (k_{ph} + k_{sp})(k_{ph}^2 + k_{sp}^2) \right) \times$$

$$(k_{ph} - k_{sp})(k_{ph} + k_{ph} + k_{sp})^2$$

(14)

The final equation is the overlapped area from the circles, arranged in MATLAB code. This code is written for determining the rate of coupling of photons in free space with surface plasmons. The flow chart of the algorithm for determining the area of overlapping is shown in Fig. 3.

Coupling between the surface plasmons and the emitted light from LED by using a patterned aperture can be cause to enhancing the directivity of the emitted beam. The grating period has a great effect on the directivity and the far field emission of the patterned aperture can be written as (Dikken et al., 2016):

$$E(\theta) = \frac{1}{N} \frac{\sin(N(k d \sin(\theta) + \delta)/2)}{2 \sin(k d \sin(\theta)/2)}$$

(15)

where $N$ is the number of contributing dipoles, $d$ is the distance between dipoles, $\theta$ is the angle from normal, and $\delta$ is the relative phase. The relative phase refers to the phase of the surface plasmon wave with respect to the grating elements. This phase term determined by:

$$\delta = 2\pi d/\lambda_{sp}$$

(16)

The flow chart of the algorithm for determination the directivity of the emitted beam is shown in Fig. 4.
3. RESULTS AND DISCUSSION

Variation the overlapping area between the circle of wave vector \( (k) \) of surface plasmons and incident light shifted wave vector circle versus the wavelength of the incident light, at grating period equal to 0.6 µm showed in the Table 1. The relation is approximately linear and by increasing the wavelength of light the area of overlapping will increase, this is perhaps due to that the coupling between the incident light and surface plasmons will decrease therefore enhancing the transmitted light will be better in short wavelength values. These results in a good agreement with the work done by Iwase et al. (Iwase et al., 2010). They found that the enhancement ratio increases at shorter wavelengths for Ag samples, whereas it is independent of wavelength for Al-coated samples. The PL enhancement after coating with Ag and Al can be attributed to strong interaction with surface plasmons.

This study indicated that the incident wavelength which was 548.7nm (emitted from GaP p-n junction) gives an area of overlapping equal to \( 0.0241 \times 10^{-4} \) µ². According to Fig. 5 this relation for a grating period equal to 600 nm, it is appear that this value of area of overlapping has a small value according to the longer wavelengths which is corresponded to a better coupling.

| Energy gap(eV) | Lambda | Area/µ²\times10^{-4} |
|---------------|--------|----------------------|
| 1.5           | 826.7  | 9.6722               |
| 1.6           | 775    | 8.4298               |
| 1.7           | 729.4  | 7.4057               |
| 1.8           | 688.9  | 6.5529               |
| 1.9           | 652.6  | 5.8362               |
| 2             | 620    | 5.2287               |
| 2.1           | 590.5  | 4.7096               |
| 2.2           | 563.6  | 4.2628               |
| 2.26          | 548.7  | 4.0241               |
| 2.3           | 539.1  | 3.8757               |
| 2.4           | 516.7  | 3.5382               |
| 2.5           | 496    | 3.2424               |
| 2.6           | 476.9  | 2.9816               |
| 2.7           | 459.3  | 2.7507               |
| 2.8           | 442.9  | 2.5452               |
| 2.9           | 427.6  | 2.36117              |
| 3             | 413.3  | 2.1971               |

The overlapping area of the two circles of the incident light propagation constant and shifted surface plasmon propagation constant will increase
with increasing the grating period. This is due the coupling which increase by increasing the \( k \) value of grating which is an indicator for decreasing the value of grating period \( \Lambda (\Lambda=2\pi/k) \). The overlapping area is increased more rapidly till the grating period reach 500nm (Fig. 6).

The results found in this study, regarding the variation of coupling between free space photons and surface plasmons with grating period (Fig. 7), in general, are in an acceptable agreement with the results found by Okamoto et al. \((Okamoto et al., 2007)\) for grating period 0-800 nm. On the other hand, the results of present study are in good agreement with results of Linqing and Yanwu. \((Linqing and Yanwu, 2014)\) they stated that the intensity of radiated light increases with decreasing grating period which is again can be linked with our results in Table 2. It can be noted from Table 2 that the relation of the spread angle (theta) of emitted light and grating period are inversely related and this is highlighted in Fig. 7.

### Table 2: Relation of the spread angle of emitted light and grating period value which they directly vary At aperture of LED equal to 10µm. Lambda=548.67nm

| Grating period |
|----------------|
| Radiating Sources |
| Theta |
| 1                | 10000   | 7.17 |
| 10               | 1000    | 4.9714 |
| 25               | 400     | 4.137 |
| 55               | 181.81  | 3.4667 |
| 75               | 133.33  | 3.22 |
| 100              | 100     | 3.0062 |
| 150              | 66.66   | 2.72 |
| 175              | 57.14   | 2.62 |
| 200              | 50      | 2.5477 |
| 225              | 44.44   | 2.47 |
| 250              | 40      | 2.421 |
| 275              | 36.36   | 2.37 |
| 300              | 33.33   | 2.358 |
| 325              | 30.76   | 2.286 |
| 350              | 28.57   | 2.512 |
| 375              | 26.66   | 2.219 |
| 400              | 25      | 2.191 |
| 425              | 23.52   | 2.165 |
| 450              | 22.22   | 2.1412 |
| 475              | 21.052  | 2.119 |
| 500              | 20      | 2.099 |
Figure 7: The relationship between grating period and emitting angle.

It can be seen from Fig. 8 that the coupling increases with decreasing grating period. This, perhaps, indicates that the coupling is superior for small grating period value. In addition, through decreasing grating period the number of radiating sources for a specific aperture will increase and this cause to increasing the directionality. Therefore, in order to obtain good direction ability corresponding to the enhancing radiated intensity the proper grating period must be chosen.

Figure 8: Variation of overlapping area of with grating period for both Ag and Au grating.

Figure 9: Shifting of the circles of surface plasmon wave vector under the effect of variation of grating period for (a) d=0.9, (b) d=0.7 and (c) d=0.4.

Fig. 9 shows that the overlapping area between the two circles of photon in free space and surface plasmons increase with increasing grating period, which indicates that the coupling increase by increasing $k$-vector of grating.

In the present work the coupling between surface plasmons and the emitted photon from the LED by a patterned aperture which act as a grating used for controlling the direction of the emitted beam. Thus, grating period has a great
effect on controlling the directionality of the beam.

![Figure 10: (a) Directional radiating and (b) Polar angular distribution of intensity emitted of LED with rational number of radiating sources when grating period=350, n=16.5](image)

Fig. 10 shows the directionally controlling LED emission by surface plasmons. These results are in a good agreement with the theoretical study by Martin-Moreno et al. (Martin-Moreno et al., 2003). It can be seen that from Fig. 10 the wavelength, angle (and angular width) of emission from a sub-wavelength aperture can be modified by the introduction of surface corrugations around the aperture and the tuning of its parameters.

Similarly, Heykel et al. (Aouani et al., 2011) in their study which dealt with plasmonic antennas for directional sorting of fluorescence emission by optical antennas, which have been recently introduced as conceptual tools to control the radiation properties for nano-emitters fixed on a substrate. Same nano-antenna demonstrated simultaneously with narrow emission radiation pattern in a cone of (±15 in the direction normal to the sample).

It can be noted that the light emitted in a narrow angle matches the directionality is very suitable for small values of grating period, and this is, perhaps, due to that the small values of grating period associated with the large number of radiating sources.

4. CONCLUSIONS

In present work the coupling between photons in free space and surface plasmons studied theoretically through calculating the area of overlapping between the circles of $k$-vector for light in vacuum and surface plasmons in two dimensions. The obtained results indicated that one can compute the rate of coupling theoretically before fabricating a specific enhanced (LED). On the other hand, the SP could be geometrically tuned by fabricating nano-grating structures. Finally, by using this method, both high-efficiency and spatially controlled direction light emission is predicted for light emitters.

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