Enhancing intensity of emitted light from a ring by incorporating a circular groove

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Abstract: We fabricated a ring containing a single circular groove (RCG) on silver film and which was supported on a glass substrate. We found that by changing the mean radius of the circular groove, the light intensity emitted from the RCG can be modulated by using the scattering light from the circular groove. In addition, we also fabricated circular grooves with the same depth but of different widths so that we could examine the scattering light behavior of the grooves. Herein, we propose a theoretical model which takes into account the amplitude modulation of the cylindrical waves. Our results showed that our proposed model agreed well with the experimental results.

OCIS codes: (240.6680) Surface plasmons; (260.3160) Interference; (240.0240) Optics at surfaces.

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1. Introduction

In recent years, much research has been done studying the optical properties of metallic nanostructures. Along this field of research, many interesting developments have been discovered and developed. Using classical aperture theory, it is generally known that light beams have difficulty passing through a sub-wavelength hole when examined [1]. It is known that when light impinges on a metallic nanostructure, it produces surface plasmon on the metal surface since the nanostructure can provide the extra momentum needed to create this phenomenon. Ebbesen, *et al.*, [2] found that surface plasmon interactions can enhance the light beam intensity emitted through a hole array when a nanoscale opening is incorporated. When the light beam impinges on the hole array, the incident side provides enough spatial momentum to convert the free space light beam into the surface plasmon such that the nanostructure at the exiting side plays a role in scattering the surface plasmon into free space. This enhanced light emission contributed by the existence of the surface plasmon has been termed "extraordinary transmission" [3]. Surface plasmon waves have also been found to propagate along metal surfaces such that it scatters into free space along a certain direction [4] by adopting a corrugated nanostructure of proper grooves [5-8]. Many applications have been proposed and investigations have been undertaken with an attempt to make an appropriate metallic nanostructure which can excite the surface plasmon efficiently [9].

Previously, surface plasmon generation [10] and the interaction [11] between metallic slits have been investigated theoretically and experimentally. The intensity of the emitted light from the slits can be modulated as the distance between the slits varies. When the light beam impinges on the ring, the transmitted light possesses a behavior similar to that of a Bessel beam [12]. This means that the transmitted beam can have both a long working distance and a small focusing spot which is very different from the behavior of a Gaussian beam. If we can combine both a Bessel beam and a surface plasmon phenomenon, we can develop a very useful optical writing head for point sources [13] and nanolithography applications [14]. In our previous research work, we investigated the focusing phenomenon of metallic rings [15]. The authors [16] also have discussed the transmission properties of ring arrays.

In this paper, we investigate the optical properties of a ring with additional circular grooves such that the surface plasmon can result in scattering into free space and where the

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scattered light can interfere with the emitted light beam induced by the ring. This interference can then further modulate the intensity of the focusing spot and the distance of the RCG structure. Gay *et al*., [17] discussed the surface wave interaction between a parallel slit and groove, and proposed other propagating characteristics. In Lalanne's previous research work [18], he states that the relationship between the scattering coefficient and groove width is unlike the Fabry-Perot phenomenon, which makes qualitative analysis difficult to undertake. Lalanne also postulates that the propagating characteristic of a surface plasmon with a longer wavelength will possess a $1/\sqrt{x}$ decay where x is the propagating distance which will be a creeping wave and will be absent in visible light. In our experimental set-up, we used visible light as our light source, and extended the model to a two-dimensional problem. We also proposed the propagating characteristics of a cylindrical surface plasmon. Our circular groove was designed such that it had a proper mean radius where the emitted light from the RCG was a highly focused energy as a result of constructive interference.

2. Experimental set-up

In this paper, we created circular grooves of different widths but of the same depth in order to analyze the optical properties of the RCG quantitatively. We used a focused ion beam (FIB) to fabricate the RCG structure. We first deposited the silver film on the glass substrate using a sputtering process. We then used the FIB to mill the RCG structure directly. In order to control the groove depth accurately, all the RCG structures were fabricated on the same metal film. We fabricated the grooves with different mean radius, which varied from 2μm to 3.35μm at 0.15μm intervals. For all the circular grooves, we fabricated four corresponding groove widths at 100nm, 150nm, 200nm, and 250nm, respectively. It should be noted that we defined the mean radius as the average of the outer radius and the inner radius. In our set-up, every ring in the RCG structure had the same outer 4μm radius and opening width of 100nm. The groove depth of all the circular grooves was 55nm, and the Ag thickness was 248nm. We used a collimated diode pump laser (532nm) with a linear polarization as our light source, and adopted confocal microscopy coupled with a spectrometer to capture the intensity of light emitted from the RCG structure. We made the light incident at the silver-glass side and measured the transmission intensity from the RCG structure at the metal-air side. At a wavelength of 532nm, the surface plasmon of the propagating length and wavelength was about 9.5μm and 505nm [19], respectively. Our experimental procedure was as follows: We first used a confocal microscope to measure the focusing intensity and focusing length of the light emitted from a ring without a circular groove. By stepping the image plane away from the metal surface to a distance F, we then determined the light emitted from the ring focused to a single point. The measured F was around 8μm. We noticed then that all the intensity of the light emitted from the RCG was captured at that same distance, i.e., 8μm away from the metal surface. This measured emitted light intensity was normalized using the light intensity emitted from the ring without a circular groove.

3. Theoretical modeling

Figure 1 shows the schematic of the RCG structure. When the light beam passed through the ring, it decomposed into two components at the exiting side. The first wave propagated toward free space. The second wave propagated along the metal surface. The surface plasmon was the wave that propagated along the metal surface. We then extracted the surface plasmon at the metal surface into a photon by using a circular groove, and where additional emitting energy was obtained.

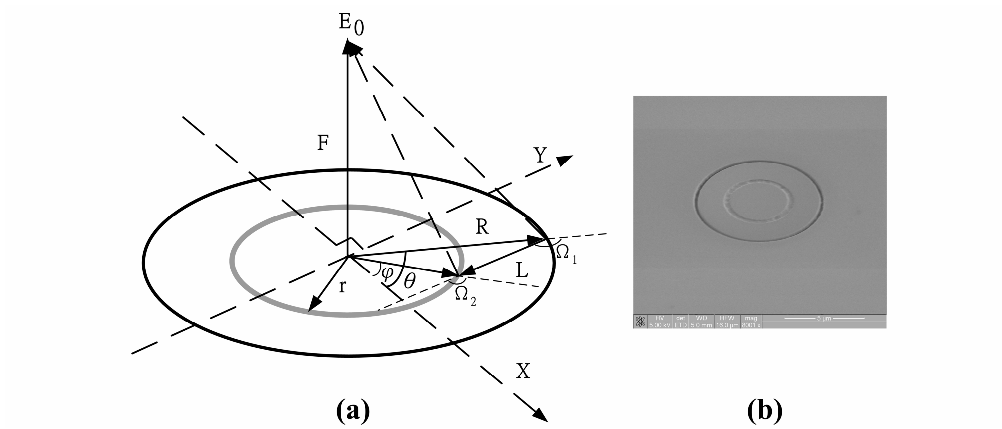

Fig. 1. Schematic of the RCG structure: (a) F is the focusing length of a single ring; R and r represent the outer and the inner mean radii; E_0 is the sum of the light scattering from the groove and the light emitted from the ring. The Y-axis coincides with the polarization direction of the incident light. (b) Scanning electron microscope photo of the RCG structure, where the outer radius and the opening width of the ring are 4μm and 100nm, respectively. The outer radius, width and depth of circular groove are 2.125μm, 250nm, and 55nm respectively. The Ag thickness was 248nm.

From our experimental set-up, we found that the transmitted light from a single ring focused at 8μm above the metal and thus we choose this specific position to study this model. The electric field E_0 was at the axis of symmetry at a distance F behind the specimen. The F represents the focus distance of the transmitted light from a single ring. The total electric field E_0 was the sum of the light from the RCG structure. According to the above, E_0 can be represented as:

$$\begin{aligned} E_0 &= E_{ring} + E_{scattering} \\ &= \int_0^{2\pi} E_{slit} \left| Sin(\theta) \right| R e^{-i\Delta_1} d\theta \; + \\ & \int_0^{2\pi}\int_0^{2\pi} \beta \frac{Cos(\Omega_1)Cos(\Omega_2)}{\sqrt{L}} E_{slit} \left| Sin(\theta) \right| e^{-\frac{L}{2L_{sp}}} e^{-i(\Delta_2+\Delta_3-\Delta_g)} r d\theta d\phi \end{aligned} \quad (1)$$

where Δ_1, Δ_2, and Δ_3 are equal to $2\pi\sqrt{R^2+F^2}/\lambda_{air}$, $2\pi L/\lambda_{SP}$, and $2\pi\sqrt{r^2+F^2}/\lambda_{air}$, respectively; Δ_g is the scattering phase lag, β is the scattering coefficient, and L_{sp} is the propagating length of the surface plasmon. In addition, L is the distance from the point source along the ring to a certain point at the groove, and θ and φ are the angles from the positive x-axis. We neglected the back-reflection of the surface plasmon at the groove because it was a very small signal due to serious decay.

As a linearly polarized light beam was used as our light source, the light distribution along the ring can be represented by $\left| Sin(\theta) \right|$. We considered two field contributions to E_0. More specifically, E_0 was assumed to be the superposition of E_{ring} and $E_{scattering}$, which represents the total electric field of the light directly emitted from the ring and the total electric field of light scattered from the circular groove, respectively. We also considered surface plasmon at each position along the ring as a point source. Using Huygen's principle, the field at any point of the groove can be viewed as the sum of the contributions from all point sources along the ring. That is, we can use the inner integration of the second term in Eq. (1) to represent the field at any point of the groove. The plasmons were launched and were found to be perpendicular to the ring [20, 21] and groove, respectively. Thus, Ω_1 and Ω_2 represent the angles between the point source propagating direction and the outward direction of the ring and outward of the groove, respectively. Furthermore, Δ_1 and Δ_3 represent the two phase differences of light after

#87906 - $15.00 USD Received 25 Sep 2007; revised 29 Oct 2007; accepted 29 Oct 2007; published 30 Oct 2007

propagating towards free space, and Δ_2 represents the phase difference after the surface plasmon propagates along the metal surface. The cylindrical wave can be represented by $1/\sqrt{L}$ [22]. During the scattering process, the scattering coefficient β and scattering phase lag Δ_g induced by the groove were taken into consideration and were determined by fitting to a curve based on the experimental data obtained. In our experimental set-up, we measured the focusing intensity of a ring without any circular groove having an outer radius of 4μm, and an opening width of 100nm which was then used to normalize the light intensities obtained from the light emitted from all other RCG structures.

4. Experimental results and discussions

When we took all the optical properties of the RCG into consideration, we obtained Δ_g and β by fitting to a theoretical model. Figure 2 shows the experimental results and the obtained fitted curve.

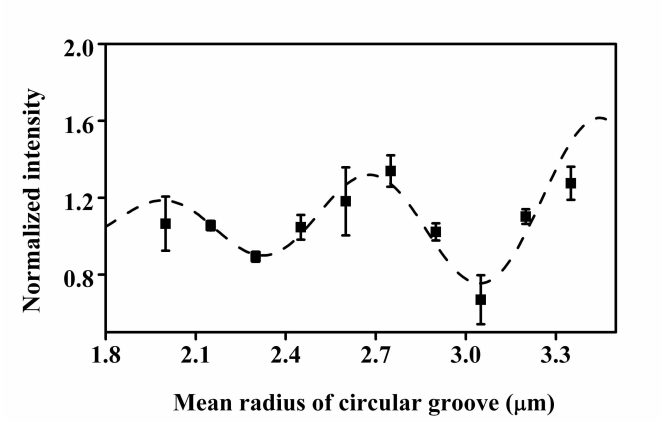

Fig. 2. Experimental results and fitted curves which represent the groove width and depth at 250nm and 55nm, respectively.

We found that the normalized intensity was modulated by changing the mean radius of the circular groove due to scattering of the interference. Our experimental results agreed well with the theoretical model, and the intensity of emitted light from the RCG structure was 20-30% higher than the intensity of the emitted light from a ring without a circular groove. Thus, our proposed theoretical model can be adapted and used to develop a straightforward approach towards utilizing RCG properties. We found that when the light beam scattered from the groove, it propagated toward the focusing spot of the RCG as it had a proper mean radius of the groove. The phase of the scattered light beam was modulated by the mean radius of the circular groove. When the RCG structure is optimized, the scattering light by a groove and the transmitted light from the ring will create a constructive interference. The transmitted beam from the RCG will have maximum intensity, and more transmitted intensity can be applied easily using photolithography. For the case when the groove is very close to the ring, we found that our model will not be applicable. Although the value is not diverging, there is strong oscillation as the groove is very close to the ring. This will result in a limitation of the model since we cannot control transmission intensity accurately. In Fig. 2, β and Δ_g of the RCG were found to be around 0.29 and 0.26π, respectively. In summary, it appears that the scattering light interference uses two parameters to examine the optical properties of the RCG structure. That is, β represents the scattering intensity, and Δ_g represents the scattering phase lag. Furthermore, we see that we can also vary Δ_g by changing the focusing length of the RCG structure. Figure 3 shows the four different kinds of circular grooves which we used in our model in order to obtain the Δ_g and β parameters.

#87906 - $15.00 USD Received 25 Sep 2007; revised 29 Oct 2007; accepted 29 Oct 2007; published 30 Oct 2007

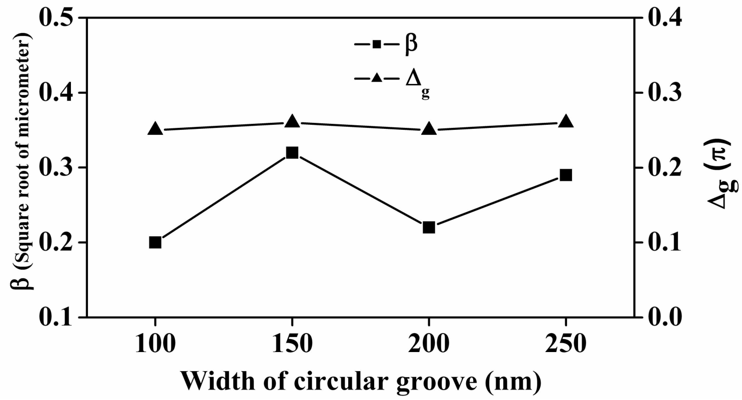

Fig. 3. β and Δ_g of the four kinds of groove widths: 100nm, 150nm, 200nm, and 250nm. (Note: the square and triangular marks represent β and Δ_g, respectively.)

We found that Δ_g changed only slightly when the width of the circular groove changed. The authors' previous work[15] also showed that the scattering phase was strongly influenced by the groove depth. This observation led us to conclude that Δ_g is strongly influenced by groove depth variations which can be attributed by the dominant effect of the vertical cavity mode. For a ring with multi-grooves, this model can also be applied and written as follows:

$$E_0 = E_{ring} + E^1_{scattering} + E^2_{scattering} + E^3_{scattering} + ...E^n_{scattering} \tag{2}$$

where n represents the number of the different grooves.

The scattering coefficient β shows a significant variation when the width of the circular groove changes and which appears sensitive to a change in the width of the circular groove. The scattering coefficient β and scattering phase lag Δ_g appears to be a very complex function of the geometry of the grooves. Therefore, from an engineering application viewpoint, if we want to control the optical properties of a RCG structure accurately, we need to choose an ideal Δ_g to control the emitted light from the RCG structure. The optimized RCG structure can be applied to many fields such as photolithography. Other potential applications include drilling high aspect ratio nanostructures [23], trapping particles [24], and read-out systems [25].

Acknowledgments

The authors appreciate the financial support from the Materials and Chemical Research Laboratory of the Industrial Technology Research Institute (ITRI) and Taiwan's National Science Council under Grant No. 95-2221-E-002-122.

#87906 - $15.00 USD Received 25 Sep 2007; revised 29 Oct 2007; accepted 29 Oct 2007; published 30 Oct 2007