Calculation of Surface Plasmon Effect on Optical Discs

Kuo Pin CHIU*, Wei Chih LIN, Yuan Hsing FU and Din Ping TSAI

Center of Nanostorage Research, National Taiwan University, Taipei 10617, Taiwan

Department of Physics, National Taiwan University, Taipei 10617, Taiwan

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We calculated the conditions of surface plasmon resonance for various optical discs to evaluate the role of periodic lands and grooves or recording mark trains as grating couplers. With the typical parameters of structure used in the discs, it is shown that surface plasmons have a weak influence on ordinary optical discs. These results differ from the situation with super-resolution near-field optical structures where surface plasmons or localized surface plasmons have a considerable influence on such discs. [DOI: 10.1143/JJAP.43.4730]

KEYWORDS: surface plasmon, optical discs

1. Introduction

The interaction of electromagnetic radiation with an interface can generate several interesting phenomena. In 1902, Wood reported the observation of a series of anomalies in spectra from ruled metallic diffraction gratings.¹⁾ One of these anomalies took the form of sharp changes in the reflected intensity of transverse magnetic (TM) polarized radiation when the grating vector was parallel to the plane of incidence. It is now well established that the “anomalous” spectra arise from the incident electromagnetic wave coupling to the surface plasmons (SPs) excited at the interface. SPs are electromagnetic excitations that propagate along the interface between a metal and a dielectric. Recently, SPs have been found to play an important role in the trapping of incident radiation into small volumes and enhancing the transmitted light through a thin film.²⁾ In 2001, Tominaga et al. mentioned the possibility of the coupling of SPs by the recorded mark trains in AgO_x-type super-resolution near-field optical structures (super-RENS).³⁾ The effect of surface plasmon resonance further enhances signal intensity. On the other hand, nanoscale noble-metal structures can exhibit anomalous optical excitation in the visible range due to a localized surface plasmon (LSP).^{4–8)} The LSP resonance positions depend mainly on the structural geometry and polarization state of incident light. LSPs were suggested to be the key factor in super-RENS.⁹⁾ In this study, we investigated SPs and LSPs that may result from the various features of compact disc (CD) and digital versatile disc (DVD). The structure of optical discs, such as periodic lands and grooves, and the recorded marks may serve as a grating coupler for an incident laser to excite SPs by providing the in-plane momentum needed to excite of SPs. The effects of these SPs may affect the readout signals in the far field and near field.

2. Basic Principle of Calculation

A surface plasmon is an electromagnetic excitation at the interface between a material with negative permittivity (often a metal) and a dielectric. It consists of a surface charge density oscillation coupled to electromagnetic fields which are bound to the surface and decay exponentially into both media. Consider a flat interface that is formed by combining a dielectric and a metal with permittivities ϵ_1 and

ϵ_2 respectively. It is possible to calculate the dispersion relations of the surface plasmon using Maxwell's equation of electromagnetic waves together with the boundary conditions of $\mathbf{E}$ and $\mathbf{H}$ fields at the interface.¹⁰⁾

$$k_x = \frac{\omega}{c} \left(\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} \right)^{1/2} \equiv k_{sp}$$

and

$$k_{zi} = \left[\epsilon_i \left(\frac{\omega}{c} \right)^2 - k_x^2 \right]^{1/2}; i = 1, 2. \quad (1)$$

In eq. (1), k_x is the wave vector of the surface plasmon along the direction parallel to the interface. k_{z1} and k_{z2} are the wave vectors of the surface plasmon in the direction perpendicular to the interface in the dielectric (with permittivity ϵ_1) and in the metal (with permittivity ϵ_2), respectively. ω is the frequency of incident light, and c is the velocity of light in a vacuum. Equation (1) shows that the k_x of the surface plasma exceeds that of incident light having the same frequency within the adjacent dielectric, as shown in Fig. 1(a). This result means that a surface plasmon on a single flat interface between a metal and a dielectric cannot be excited simply by radiating light onto that surface. To excite surface plasmons it is necessary to have an appropriate coupling geometry. For a periodically corrugated dielectric/metal interface with period a , as shown in Fig. 1(b), the wave vector of the incident light may effectively gain the integer values of the grating vector, g , of periodic corrugations. The relation can be expressed as

$$k_x = \frac{\omega}{c} \sqrt{\epsilon_1} \sin \theta + ng,$$

with

$$g = \frac{2\pi}{a} \quad \text{and} \quad n = 1, 2, 3, \dots \quad (2)$$

where θ is the incident angle of impinging light. When the k_x of impinging light differs from that of the surface plasmons by a nonzero value of the grating vector, incident light may couple to the surface plasmons.

3. Structures and Parameters of Optical Discs

Ordinary optical discs have multilayer structures containing protective layers, a recording layer, a reflective layer and a polycarbonate (PC) substrate. Figure 2 shows a schematic diagram of ordinary optical discs. The reflective layer is usually made of Al alloy, and each protective layer is made

*E-mail address: kpchiu@ntu.edu.tw

Fig. 1. (a) Dispersion curve of surface plasmons. (b) Excitation of surface plasmons by a grating coupler. The grating period is a , and the incident angle of impinging light is θ . A periodic structure can provide the in-plane momentum required for incident light of appropriate polarization to excite a surface plasmon.

of ZnS-SiO₂ composites. The recording layers of DVD recordable (DVD-R) and phase change discs are made of a dye and a phase-change alloy, respectively. The periodic land-groove structure of these discs serves as a grating coupler, which may provide the in-plane momentum needed to excite surface plasmons along the radial direction of the discs. On the other hand, the recording mark trains in the recording layer may also serve as the grating coupler in the tangential direction of the discs. In the following calculations, the dielectric constants at different wavelengths of each layered material are cited from previous reports.^{11–17)}

4. Results and Discussion

We have calculated the surface plasmon resonance conditions satisfied by various types of disc structure. All the calculations are based on the simple consideration that the interface is within two infinite media. Table I shows our calculation results in the radial direction of the optical discs. The first column is the type of disc being considered. The following λ and numerical aperture (NA) values are the corresponding laser wavelengths and numerical apertures that are typically used in each disc. Because the periodic land-groove structure exists in layers shown in Fig. 2 for the different types of disc, we consider each interface separately in Table I. The quantity $k_{x,\max}$ is the maximum k_x of incident light, as seen in Fig. 3(a). It is calculated using

Fig. 2. Schematic diagram of the structure of optical discs: (a) CD, (b) DVD-R and (c) phase-change discs, such as CD-RW, DVD-RAM, DVD-RW and DVD+RW.

$$k_{x,\max} = \frac{2\pi}{\lambda} \times \text{NA}. \quad (3)$$

With the incident angle of the focused laser beam ranging from zero to the maximum angle, θ_{NA} , k_x ranges from zero to $k_{x,\max}$ for a given NA. Because the dielectric constants adopted are complex numbers,^{11–17)} the k_{sp} , k_{z1} and k_{z2} calculated from eq. (1) are also complex. The real part of these quantities is denoted by an additional “-r” in the lower index, and the imaginary part is denoted by an additional “-i” in the lower index as can be seen in the first row of Table I. The real parts of k_{sp} and k_z represent the propagating properties of surface plasmon waves, and the imaginary parts of k_{sp} and k_z are related to the dissipation of electromagnetic energy.

The $a_{\max}$ in the table is the maximum period in the land-groove structure, i.e., the maximum track pitch, which allows incident light to excite the surface plasmons at the corresponding interface. It is calculated using

$$k_{\text{sp-r}} = k_{x,\max} + \frac{2\pi}{a_{\max}}, \quad (4)$$

where $k_{\text{sp-r}}$ and $k_{x,\max}$ are those calculated previously. This relation comes from eq. (2) by adopting $n = 1$; that is, we consider the first-order diffraction of incident light only. Because the k_x of incident light with the given NA is smaller than $k_{x,\max}$, the track pitch must be smaller than $a_{\max}$ to allow

Table I. Calculation results of surface plasmon resonance conditions for optical discs in the radial direction.

Disk	λ (nm)	NA	Track pitch (μm)	interface	$k_{x,\text{max}}$ ($\times 10^6 \text{ m}^{-1}$)	$k_{\text{sp-r}}$ ($\times 10^6 \text{ m}^{-1}$)	$k_{\text{sp-i}}$ ($\times 10^6 \text{ m}^{-1}$)	k_{z1-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z1-i} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-i} ($\times 10^6 \text{ m}^{-1}$)	a_{max} (μm)	$\sin \theta_{\text{min}}$ ($a = \text{track pitch}$)
CD-ROM	780	0.45	1.6	Al/PC	3.623	12.886	0.155	15.035	58.346	0.752	-2.652	0.678	1.113
				ZnS-SiO ₂ /Al	5.934	22.510	0.480	1.482	-7.289	10.720	67.311	0.379	1.418
DVR-R	635	0.6	0.74	Al/Dye	5.934	...	...	...	...	...	...	...	...
				Dye/PC	5.934	...	...	...	...	...	...	...	...
				PC/Al	3.623	12.886	0.155	0.752	-2.652	15.035	58.346	0.678	1.113
CD-RW	780	0.45	1.6	Al/ZnS-SiO ₂	3.623	17.743	0.404	14.654	59.511	1.455	-4.929	0.445	1.716
				ZnS-SiO ₂ /GST	3.623	16.782	0.718	4.357	-2.766	43.486	33.140	0.477	1.597
				ZnS-SiO ₂ /PC	3.623	10.161	0.000	13.756	0.000	7.505	0.000	0.961	0.774
				PC/Al	5.796	15.629	0.165	0.716	-3.596	11.640	6.561	0.639	0.739
DVD-RW	650	0.6	0.74	Al/ZnS-SiO ₂	5.796	21.861	0.451	11.239	67.294	1.439	-6.858	0.391	1.384
				ZnS-SiO ₂ /GST	5.796	20.558	1.109	5.399	-4.222	44.333	43.115	0.426	1.249
				ZnS-SiO ₂ /PC	5.796	12.286	0.000	16.786	0.000	8.993	0.000	0.968	0.393
				PC/Al	5.934	16.025	0.173	0.730	-3.796	11.139	65.500	0.623	0.762
	635	0.6	0.74	Al/ZnS-SiO ₂	5.934	22.510	0.480	10.720	67.311	1.482	-7.289	0.379	1.418
				ZnS-SiO ₂ /GST	5.934	26.176	2.284	8.884	-6.730	42.155	45.393	0.310	1.788
				ZnS-SiO ₂ /PC	5.934	13.462	0.000	23.074	0.000	7.854	0.000	0.835	0.503
				PC/Al	5.796	15.629	0.165	0.716	-3.596	11.640	6.561	0.639	0.560
DVD-RAM	650	0.6	0.615	Al/ZnS-SiO ₂	5.796	21.861	0.451	11.239	67.294	1.439	-6.858	0.391	1.205
				ZnS-SiO ₂ /GST	5.796	20.558	1.109	5.399	-4.222	44.333	43.115	0.426	1.071
				ZnS-SiO ₂ /PC	5.796	12.286	0.000	16.786	0.000	8.993	0.000	0.968	0.214
				PC/Al	5.796	15.629	0.165	0.716	-3.596	11.640	6.561	0.639	0.560

Fig. 3. Schematic diagram of an incident laser beam (wavelength λ) focused by an objective (NA, $1 \times \sin \theta_{NA}$) on an optical disc. (a) The x -direction is along the radial direction of the disc. (b) The x -direction is along the tangential direction of the disc.

the laser beam to excite surface plasmons at the interface. On the other hand, if the period of the land-groove structure is set to the typical value of track pitch, the incident angle must be greater than some minimum value for the laser beam to excite surface plasmons of the interface. This minimum angle can be calculated using

$$k_{sp-r} = \frac{2\pi}{\lambda} \times \sin \theta_{\min} + \frac{2\pi}{\text{track pitch}}, \quad (5)$$

where the values of k_{sp-r} , λ and track pitch are given in the table. Similar to the calculation of $a_{\max}$, in eq. (5), we consider only the first-order diffraction of incident light. It should be noted that, when the laser beam is focused by the objective in air, the $\sin \theta_{\min}$ obtained using eq. (5) is the minimum NA needed to excite surface plasmons at the corresponding interface.

From the results of $a_{\max}$ in Table I, it can be seen that for typically used parameters of some optical discs, such as CD read-only-memory (CD-ROM), DVD-R and CD rewritable (CD-RW), there will be no surface plasmon effect at every interface. However, it is possible to excite surface plasmons at the ZnS-SiO₂/PC interface in DVD rewritable (DVD-RW) and at the ZnS-SiO₂/PC and PC/Al interfaces in DVD random-access-memory (DVD-RAM) because the track pitch in these instances is smaller than $a_{\max}$. When considering the values of $\sin \theta_{\min}$ in Table I, we find that, by changing NA, it is possible to excite surface plasmons at some additional interfaces other than the interfaces described above. If we can increase the NA of CD-RW to 0.774, surface plasmons may be excited at the ZnS-SiO₂/PC interface of the disc. Results show that the NA is increased to 0.739 for a laser wavelength of 650 nm, or to 0.762 for a laser wavelength of 635 nm, and that surface plasmons can be excited at the PC/Al interface of the DVD-RW disc as well.

We also calculated the surface plasmon resonance conditions in the tangential direction of various optical discs. The calculation results are shown in Table II. Because there is no periodic land-groove structure in the tangential direction of the disc, the recording mark trains can serve as grating couplers. Because the recording mark trains are located in the PC layer of CD and in the phase-change alloy recording layer, such as in GeSbTe of DVD-RW, we consider only the Al/PC interface for CD and ZnS-SiO₂/GeSbTe interface for phase change discs, as shown in

Table II. Calculation results of surface plasmon resonance conditions for optical discs in the tangential direction.

Disk	λ (nm)	NA	Minimum pit length (μm)	interface	$k_{x,\max}$ ($\times 10^6 \text{ m}^{-1}$)	k_{sp-r} ($\times 10^6 \text{ m}^{-1}$)	k_{sp-i} ($\times 10^6 \text{ m}^{-1}$)	k_{z1-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z1-i} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-i} ($\times 10^6 \text{ m}^{-1}$)	$a_{\max}$ (μm)	$\sin \theta_{\min}$ ($a = 2 \times \text{min. pit length}$)
CD-ROM	780	0.45	0.8	Al/PC	3.623	12.886	0.155	15.035	58.346	0.752	-2.652	0.678	1.113
CD-RW	780	0.45	0.834	ZnS-SiO ₂ /GST	3.623	16.782	0.718	4.357	-2.766	43.486	33.140	0.477	1.617
DVD-RW	650	0.6	0.4	ZnS-SiO ₂ /GST	5.796	20.558	1.109	5.399	-4.222	44.333	43.115	0.426	1.315
	635	0.6	0.4	ZnS-SiO ₂ /GST	5.934	26.176	2.284	8.884	-6.730	42.155	45.393	0.310	1.853
DVD-RAM	650	0.6	0.42-0.437	ZnS-SiO ₂ /GST	5.796	20.558	1.109	5.399	-4.222	44.333	43.115	0.426	1.354-1.384

Table III. Calculation results of surface plasmon resonance conditions for super-RENS discs: (a) is in the radial direction and (b) is in the tangential direction.

Disk	λ (nm)	NA	Track pitch (μm)	interface	$k_{x,\text{max}}$ ($\times 10^6 \text{ m}^{-1}$)	$k_{\text{sp-r}}$ ($\times 10^6 \text{ m}^{-1}$)	$k_{\text{sp-i}}$ ($\times 10^6 \text{ m}^{-1}$)	k_{z1-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z1-i} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-i} ($\times 10^6 \text{ m}^{-1}$)	a_{max} (μm)	$\sin \theta_{\text{min}}$ ($a = \text{track pitch}$)	θ_{min} ($a = \text{track pitch}$)
super-RENS (Sb type)	650	0.6	0.74	PC/SiN	5.8	12.180	0.000	9.724	0.000	16.835	0.000	0.985	0.382	22.458
				SiN/Sb	5.8	20.830	0.985	4.466	-4.593	28.966	58.781	0.418	1.276	$\times$
				SiN/GST	5.8	20.077	1.032	6.356	-3.260	45.639	43.952	0.440	1.199	$\times$
super-RENS (AgO _x type)	650	0.6	0.74	PC/ZnS-SiO ₂	5.8	12.286	0.000	9.589	0.000	17.391	0.000	0.969	0.393	23.141
				ZnS-SiO ₂ /AgO _x	5.8	12.626	0.118	17.147	-0.087	10.247	0.237	0.920	0.428	25.341
				ZnS-SiO ₂ /GST	5.8	20.558	1.109	6.622	-3.442	45.507	44.035	0.426	1.248	$\times$
(a)														
Disk	λ (nm)	NA	Minimum pit length (μm)	interface	$k_{x,\text{max}}$ ($\times 10^6 \text{ m}^{-1}$)	$k_{\text{sp-r}}$ ($\times 10^6 \text{ m}^{-1}$)	$k_{\text{sp-i}}$ ($\times 10^6 \text{ m}^{-1}$)	k_{z1-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z1-i} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-r} ($\times 10^6 \text{ m}^{-1}$)	k_{z2-i} ($\times 10^6 \text{ m}^{-1}$)	a_{max} (μm)	$\sin \theta_{\text{min}}$ ($a = 2 \times \text{min. pit length}$)	θ_{min} ($a = 2 \times \text{min. pit length}$)
super-RENS (Sb type)	650	0.6	0.05-0.2	SiN/GST	5.8	20.077	1.032	6.356	-3.260	45.639	43.952	0.440	0-0.452	0-26.872
super-RENS (AgO _x type)	650	0.6	0.05-0.2	ZnS-SiO ₂ /GST	5.8	20.558	1.109	6.622	-3.442	45.507	44.035	0.426	0-0.502	0-30.132
(b)														

Table II. In this case, we view the minimum pit length of the recording marks as one-half the period of the grating structure.

The calculations of $k_{x,\text{max}}$, k_{sp} , k_{z1} , k_{z2} and a_{max} in Table II use the same relations as the calculations in the case of the radial direction. For the calculation of $\sin \theta_{\text{min}}$, we also use the eq. (5), but replace the track pitch with double the minimum pit length. As in the discussion on surface plasmon resonance condition in the radial direction, surface plasmons can be excited at the corresponding interface when the minimum pit length is smaller than one-half the a_{max} . As the results show in Table II, it can be seen that there is no surface plasmon effect on the interfaces of the ordinary optical discs in the tangential direction as well.

For the purpose of comparison, we also calculate the surface plasmon resonance conditions for two types of super-RENS discs using antimony (Sb) and silver oxide (AgO_x) as the active layers. Table III(a) shows the results in the radial direction of the super-RENS discs. We can see that there are surface plasma modes at the PC/SiN interface of Sb-type super-RENS and at PC/ZnS-SiO₂ and ZnS-SiO₂/AgO_x interfaces of AgO_x-type super-RENS. For the tangential direction, the results are shown in Table III(b). Because the minimum pit length of the recording mark train in super-RENS disc can be very small (ranging from 50 nm to 200 nm), the surface plasmons will be excited in both types of super-RENS disc.

Because the surface plasmon can propagate along the interface, it will dissipate the energy density of the focusing spot, and it may also increase the crosstalk between signals.^{18–21)} The carrier-to-noise ratio (CNR) of the disc can be seriously affected by the interactions of surface plasmons. The absence of the interactions of surface plasmons should be one of the guidelines for commercial discs. However, for the recently developed ultrahigh-density optical disc such as the super-RENS,^{3,5–9)} the working mechanism of near-field optical recording results from the influence of localized surface plasmons. The signal intensities of nanoscale marks are considered to be enhanced by localized surface plasmons. The details of the thickness of layered materials, the size and shape of local structures and the localized interactions of the random distribution have a considerable influence on the generation of the localized surface plasmons.^{5–9)} The read and write properties of optical signals are strongly related to localized surface plasmons in the case of the super-RENS. The destruction and construction of the interactions of surface plasmons are different for various types of disc structure. The advantages and disadvantages of the surface plasmon and localized surface plasmon effects are mixed and very structure-dependent.

5. Conclusions

We have calculated the wave vectors (k_{sp}) of surface plasmon at each interface of different optical discs. The maximum period (a_{max}) or minimum NA ($\sin \theta_{\text{min}}$) required to excite surface plasmons on several discs has been calculated. For the generally used parameters, only DVD-RAM has surface plasmon modes in the radial direction of the disc at the PC/Al interface. There are some modes of surface waves in the radial directions of DVD-RW and

DVD-RAM as well. Because the surface plasmons may decrease the CNR of disc, they are not found in the formats and parameters used by commercial discs, as we expected. A super-resolution optical disc with a nanometer scale track pitch and pit length may experience the surface plasmon effect, and localized surface plasmons are definitely needed for nanooptical interactions and the surmounting of surface plasmons.

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