NOVEL OPTICAL SURFACE PLASMON PROPAGATING ALONG A METAL with NANO-DIELECTRIC PARTICLES

Shigehiko NONAKA[1], Koichi KAWAJIRI[1], Hirokazu YASUBA[1], and S.T. IVANOV[2]

1):Toyota Technological Institute, Hisakata 2-12, Tempaku, Nagoya 468-8511, Japan. nonaka@toyota-ti.ac.jp

2):Faculty of Physics, Sofia University, BG-1164, Sofia, Bulgaria

In this study, novel optical surface plasmon propagating along a metal surface with nanometer-size dielectric particles such as porous in Silicon, are newly discovered analytically by solving Maxwell equations. This novel surface mode is responsible for a dipole resonance of electrons in the metal around an individual dielectric particle. The new surface mode may be available for construction of narrow band-pass filters in WDM optical communication.

1. Introduction

Effects of nano-particles on optical wave propagations have recently attracted great interest in various field of researches, for examples, UV Laser without cavity using ZnO semiconductor powder dispersed in Sol-Gel solid hosts [1], and light emission from porous silicon [2].

This paper deals with new characteristics of optical surface plasmons propagating along a metal which contains many small nano-meter size dielectric particles such as a porous silicon. We analytically discovered a novel surface plasmon in addition to a normal surface plasmon, by solving Maxwell equations. The results obtained will shed some light on mechanism interpretations of light emission from porous silicon and UV Laser and construction of narrow band-pass filters in WDM communication.

2. Modeling for Nano-Particle Optical Surface-Waveguide

Fig.1 shows a surface-wave guiding model considered here, where a rectangular coordinates (x, y, z) are used for analysis. In this model, two semi-infinite regions are interfaced at x = 0. The region for x>0 is a dielectric region with a relative dielectric constant K_g, whereas the other one for x<0 is for a metallic material with a relative dielectric constant $K_m = 1 - N$, where $N = (\omega_p/\omega)^2$, and $\omega_p^2 = n_e e^2/m\varepsilon_0$: a square of electron plasma frequency, n_e: electron density, and ω : an optical wave frequency, respectively. Here we assume that the metal contains many dielectric particles (like as porous in Silicon) with a relative dielectric constant K_d, which are distributed uniformly inside the metal region.

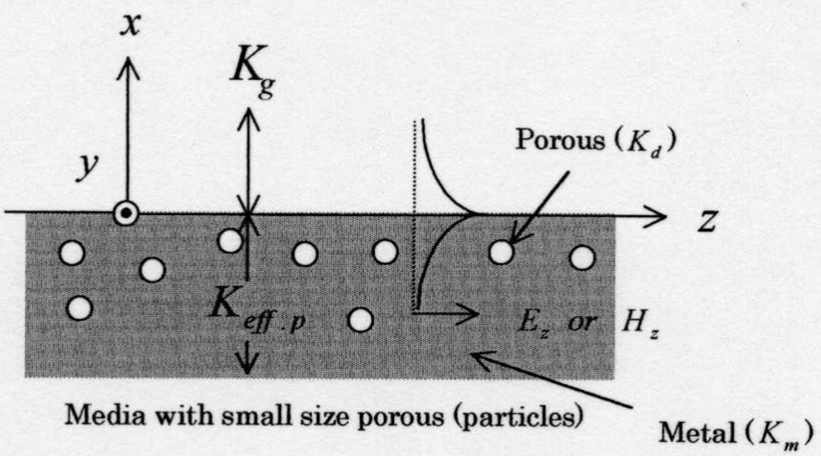


Fig.1: Semi-infinite Metal Surface-wave Guide with nano-size porous or dielectic particles.
(K_d: relative dielectric constant of porous, $K_{eff.p}$: macroscopic dielectric constant)

When applying a Wagner's theory, an equivalent macroscopic dielectric constant for the mixture of the metal and particles is expressed, as follows;

$$K_{eff.p} = K_m \left\{ \frac{2K_m + K_d + 2\delta\left(K_d - K_m\right)}{2K_m + K_d - \delta\left(K_d - K_m\right)} \right\} \qquad (1)$$

where

$$\delta = N_D^*(4\pi/3)\left(D/R^*\right)^3 \qquad (\ll 1), \qquad (2)$$

the values N_D^* and D are the density and radius of the spherical particles when setting R^* = 1 cm, respectively, and then the δ value is a volume ratio of the particles.

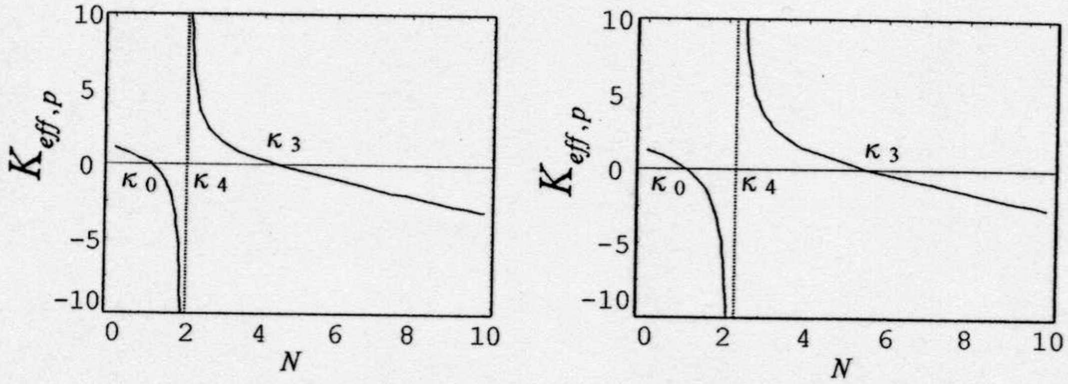
Next, Eq. (1) is further simplified as follows;

$$K_{eff.p} \approx \frac{\delta_0\left(\kappa_0 - N\right)\left(\kappa_3 - N\right)}{\left(\kappa_4 - N\right)} \qquad (3)$$

where

$$\delta_0 = 2(1-\delta)/(2+\delta), \qquad \kappa_0 = K_\infty = 1,$$

$$\kappa_3 \equiv K_\infty + \{(1+2\delta)/2(1-\delta)\}K_d, \qquad \kappa_4 \equiv K_\infty + \{(1-\delta)/(2+\delta)\}K_d$$



(a): $(\delta = 0.3\ ,\ K_d = 3.0)$ (b): $(\delta = 0.3\ ,\ K_d = 4.0)$

Fig. 2: $K_{eff,p}$ as a function of $N\,(= \omega_p^2/\omega^2)$.

Fig. 2 shows a relation between $K_{eff,p}$ and N, where the value $K_{eff,p}$ has a pole at N = κ_4 and two zero points at N = κ_0 and κ_3. Thus, the $K_{eff,p}$ value has two negative regions with the variation of N, depending on δ and K_d.

3. Dispersion Relation

When we assume that a surface wave can propagate in the z direction in the form of exp{ j(ω t - β z)}, and the wave fields are uniform in the y-direction, where ω and β are a wave frequency and a propagation constant of the wave, respectively. Imposing continuity boundary conditions on tangential components of both electric and magnetic fields of the wave yields dispersion equations for TM and TE modes, as follows;

$$-\frac{U_g}{K_g} = \frac{U_{eff,p}}{K_{eff,p}} \quad \cdots \text{ (for TM)} \tag{4}$$

$$-U_g = U_{eff,p} \quad \cdots \text{ (for TE)} \tag{5}$$

where $U_{eff,p} = \sqrt{\beta^2 - k_0^2 K_{eff,p}}$, $U_g = \sqrt{\beta^2 - k_0^2 K_g}$, $k_0 = \omega\sqrt{\varepsilon_0 \mu_0}$,

$\beta_g^2 = k_0^2 K_g$, $\beta^* = \beta / \beta_g$: an normalized wave number

The above equations can be solved numerically for the value N as a function of a square of normalized wavenumber β^{*2}.

Fig. 3 shows solutions of Eq. (4) for N as a function of β^{*2}, which means a so-called dispersion relation curve for the TM wave. In this figure, SW^N mode means a dispersion relation for normal surface plasmon which can propagate along a metal surface in a range of $\kappa_3 < N < \infty$. In particular, it is noted here that a solution for SW^J newly appears in a range of $\kappa_0 < N < \kappa_4$. This novel surface mode, SW^J, is resulted from a dipole resonance of electrons around each dielectric particle, because the dipole resonance will take place the propagation owing to the jumping between adjacent nano-dielectric particles

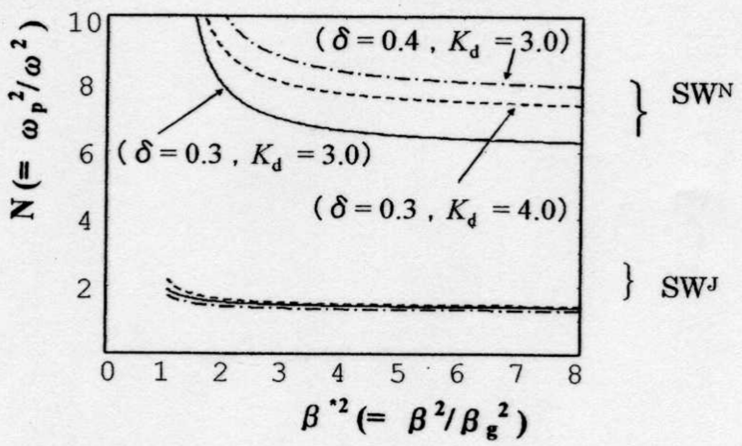


Fig.3: Dispersion relations between β^{*2} and N. $(K_g = 1.2\ , \beta_g a = 2.0)$
(The line parameters δ and K_d for SW^J correspond to the same ones for SW^N)

On the other hand, Eq. (5) for TE mode has not any solutions; that is, there are no surface waves for the TE mode in the present semi-infinite waveguide system.

5. Conclusion

We discovered a novel surface plasmon which can propagate due to a dipole resonance jumping between nano-dielectric particles. The new surface mode may contribute to construction of narrow band-pass filters for WDM optical communication.

References;

1) I. Kakiki, et al; Trans. IEICE, vol. J82-C-1, no.7(1999)

2) "Light Emission from Novel Si Materials", ed. Y. Kanemitsu et al (Physical Society of Japan, Tokyo, 1994)