A Metamaterial Structure Composed of Wire Mesh with Conducting Sphere and Its Application to Surface Plasmon

Yujiro KUSHIYAMA, Toru UNO, Takuji ARIMA
Depertment of Electrical & Electronics Engineering, Tokyo University of Agriculture & Technology
2-24-16, Nakachou, Koganei-shi, Tokyo, 184-8588, Japan
E-mail:50008645210@st.tuat.ac.jp

1. Intruduction

In recent years, the metamaterial technologies have been developed in fields of antenna and microwave engineerings. The metamaterial is a general term for materials which indicate electric properties that may not be found in nature (i.e., negative refraction index), and is usually realized by using artificial periodic structures. One of which is a three–dimensional conducting wire mesh structure. The electric property of the this structure can basically be modeled by a homogeneous medium which indicates Drude dispersion [1], and the permittivity becomes negative in the frequency range lower than a plasma frequency. Therefore, this structure has some potential for supporting surface plasmon polaritons(SPPs). The SPPs propagate at an interface between two materials having oppositely signed permittivity. Since the wave length of the SPP is smaller than that of an incident wave [2], it may be applied for sensing and imaging. However, the dispersive relation of the wire mesh structure indicates anisotropic property [3], [4]. In this paper, we propose a new metamaterial structure which realize an isotropic property. The proposed structure consists of wire mesh with a conducting sphere. The dispersion relations are confirmed by computing the reflection coefficients from the structure in Kretschmann geometry.

2. Proposed structure

Fig. 1 shows an unit cell of the proposed structure. The model is consisted with crossing wires and conducting spheres connected at the mid–points of the wires. The conducting spheres is expected to reduce the spatial dispersion of the longitudinal mode [5]. The size of the unit cell is 15 [mm]×15 [mm]× 15 [mm], the radius of the wire is $r = 0.5$ [mm], a cubic joint section is also added, its side length is 1.5 [mm], and the radius of the sphere is 2.5 [mm]. Fig. 2 shows two different interfaces considered in this paper.

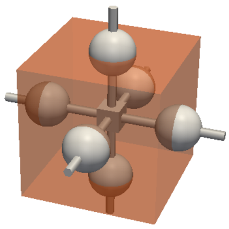

Figure 1: The unit cell of the proposed structure

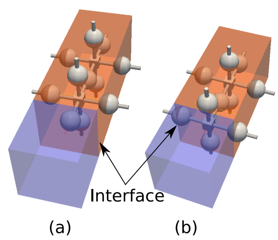

Figure 2: Two interfaces of the proposed structure

3. Numerical simulation

All numerical simulations are performed by using FDTD method. To compute the dispersion relations of the model, we set the computational region to the unit cell and Bloch's boundary conditions are applied at x, y, z directions respectively. The Bloch's wave vector is taken through the higly symmetrical points of the reciplocal space of cubic, that is $\Gamma = \pi/a(0,0,0)$, $X = \pi/a(1,0,0)$, $M = \pi/a(1,1,0)$,

$R = \pi/a(1, 1, 1)$. The computational region of the dispersion relation of the SPPs is terminated with PML in x direction, and is applied Bloch's boundary condition in y, z directions. The computational space is partitioned into two medium. One of which is filled with an air, and the other is filled with the metamaterial proposed above.

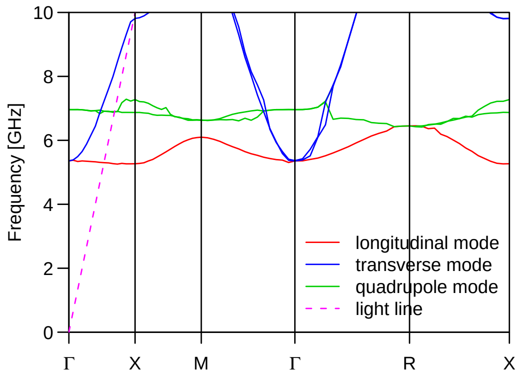

Figure 3: The dispersion relations of the proposed structure

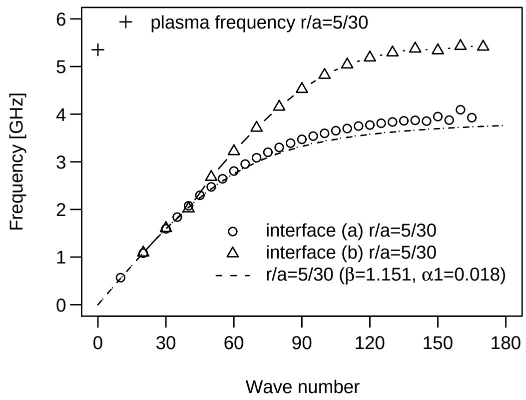

Figure 4: The dispersion relations of the surface plasmon polaritons

Fig. 3 shows the dispersion relations of the proposed structure. The spatial dispersion coefficients can be obtained by fitting the band structure to eq. (1) near Γ point [3]:

$$\omega^2 = \omega_p^2 + Ak^2c^2 \tag{1}$$

where A is a constant, and for the longitudinal mode: $A = -\alpha_1/\beta$, and for the transverse modes: $A = (1 - \alpha_2)/\beta$, where β is a polarization coefficient. From the dispersion relation of Fig. 3, we can obtain the coefficients as $\alpha_1 = 0.018$, $\beta = 1.151$. Therefore the spatial dispersion coefficients are negligibly small. Fig. 4 shows the dispersion relations of the SPPs at the interface. The SPPs are excited by the H–polarized wave. In Fig.4 the dispersion relation of the SPPs were obtained by solving Maxwell's equations on the surface:

$$k_{\mathrm{SP}} = \sqrt{\frac{\varepsilon(\omega)\varepsilon_d}{\varepsilon(\omega) + \varepsilon_d}}k_0 \tag{2}$$

where $\varepsilon(\omega)$ is a permittivity of the metamaterial accounting for the spatial dispersion [4], ε_d is a permittivity of the vacuum, and k_0 is a wave number in the vaccum. It is found that the eq. (2) agree well with the dispersion relation of interface (a). However, the dispersion relation of intreface (b) is not agree with the relation from eq. (2). It is clear that the interface of the metamaterial highly affects the dispersion relations of the SPPs.

4. Excitation of the surface plasmons

In this section, we will discuss the excitation of the SPPs, which is predicted from the dispersion relations. Fig. 5 shows the dispersion relations of the SPPs and the air. A wave number of the SPP is longer than a wave number in the air. The SPPs cannot be excited by an incident wave. However, a wave number of the evanescent wave is given by

$$k = k_0\, n\, \sin(\theta) \tag{3}$$

where k_0 is wave number in the air, θ is incident angle and n is refractive index. Therefore, the wave number can be larger than k_0 when $n\,\sin\theta > 1$. The evanescent wave at $n = \sqrt{4.0}$, $\theta = 50$ [deg] is shown in Fig. 5. The dispersion relations of the SPPs and the evanescent wave have the same value at frequency $f = 3.6$ [GHz], the SPPs can be excited at the frequency. Fig. 6 shows Kretschmann geometry. The incident wave propagate in the medium whose refractive index $n = \sqrt{4.0}$, and incident into the interface

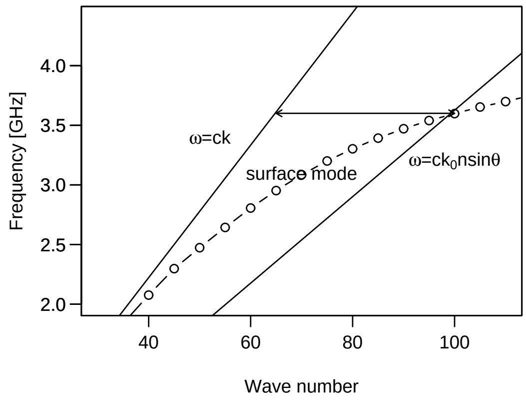

Figure 5: The dispersion relations of the SPP

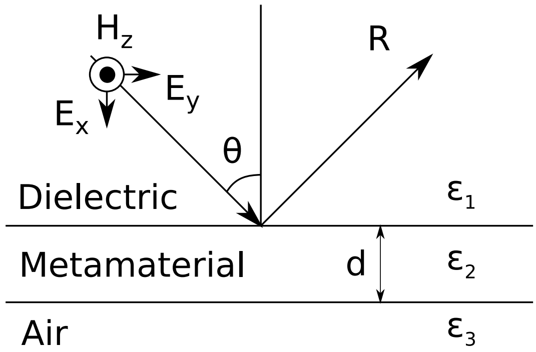

Figure 6: Kretschmann geometry

between the air and the metamaterial shown in Fig. 2 (a). The evanescent waves couple to the SPPs at the metamaterial/air interface. The SPPs propagate along the interface and the reflectivity at the coupling frequency has a minimum value. The reflectivity of the geometry is simulated by using FDTD method and Bloch's boundary condition with wave number $k_y = \omega n \sin\theta / c$, where ω is the frequency of the incident wave and c is the speed of light. The incident wave is given as a plane wave with phase shift $e^{i2\pi k_y y}$.

In our simulation, because we assumed that the structure is lossless and infinite along the interface, the SPPs reflect back to the incident plane after certain time. Therefore we used an average value during the computational periods. Fig. 7, Fig. 8 shows the time evolution of the reflectivity at the metamaterial thickness with 1 period and 2 period respectively. The minimum reflectivity at 1 period appeared around $f = 3.75$ [GHz], which is higher than the predicted value. The minimum reflectivity at 2 period appeared around $f = 3.6$ [GHz], which corresponds to the predicted value. The figures show a decreasing of a dip of the reflectivities with time. The dip vanishes after certain time. However, considering losses and finite structure, the dip in the reflectivity will be measured experimentally. Moreover, the figures predict Goos–Hänchen shift that can be observed with beam incidence. When the wave is incident to the SPPs and reflect back, the focus of the reflected beam is largely shifted. The presence of materials near the interface affects the SPPs and the shift of the beam reflection. Therefore the proposed structures could be used for sensing even 1 period thickness.

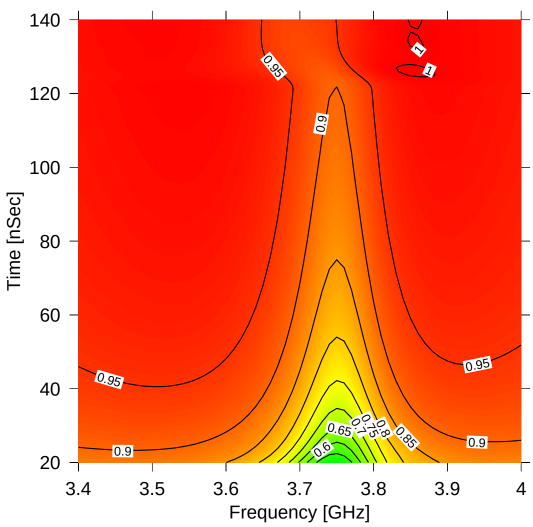

Figure 7: The reflectivity at 1 period thickness, refractive index $n = \sqrt{4.0}$, and incident angle $\theta = 50$ [deg]

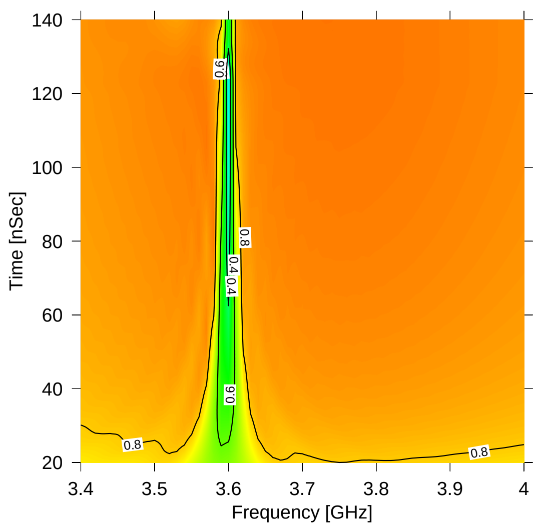

Figure 8: The reflectivity at 2 period thickness, refractive index $n = \sqrt{4.0}$, and incident angle $\theta = 50$ [deg]

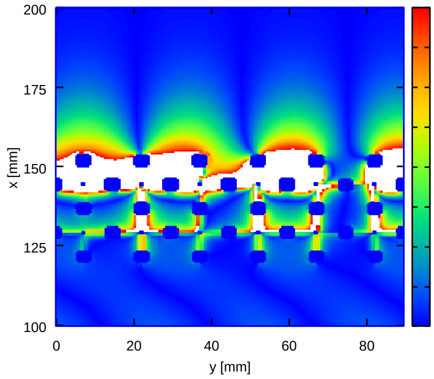

Figure 9: The magnetic fields $|H_z|$ along the metamaterial/air interface

Fig. 9 shows the magnetic field $|H_z|$ over a surface in the xy plane through the center of the unit cell of the metamaterial. Here, $f = 3.60$ [GHz], $\varepsilon_1 = 4.0$, $\theta = 50$ [deg], and $t = 95$ [ns]. The figure indicates that magnetic fields are highly confined within the surface of the metamaterial/air interface.

5. Conclusion

The dispersion relations of the wire–mesh structure with conducting sphere are numerically studied. It has been shown the spatial dispersion coefficientsis is negligible, and the dispersion relations at the interface is coinside with that of the macroscopic relation. The excitation of the SPPs were confirmed using Kretschmann's geometry. The minimum reflection occours at the frequency were predicted from the dispersion relations of the SPPs.

References

[1] J. B. Pendry, A. J. Holden, W. J. Stewart and I. Youngs, "Extremely-Low-Frequency Plasmons in Metallic Mesostructures," Phys. Rev. Lett. Vol. 25, 4773, 1996.

[2] R. Raether, "Surface Plasmons," Springer–Verlag, Berlin, 1988.

[3] M. A. Shapiro, G. Shvets, J. R. Sirigiri and R. J. Temkin, "Spatial dispersion in metamaterials with negative dielectric permittivity and its effect on surface waves," Optics Letters, Vol. 31, No. 13, July 2006.

[4] A. Demetriadou and J. B. Pendry, "Taming spatial dispersion in wire metamaterial," Journal of Physics: Condensed Matter, Vol. 20, 2008.

[5] Y. Kushiyama, T. Uno, T. Arima, "FDTD Analysis of Lattice Structure Metamaterials," IEICE Technical Report, AP2008-206, Feb. 2009.