

Ideas, Inspirations and Hints Those I Met in the Research of Electromagnetic Theory

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SUMMARY “How to get the original ideas” is the fundamental and critical issue for the researchers in science and technology. In this paper, the author writes his experiences concerning how he could encounter the interesting and original ideas of three research subjects, i.e., the accelerating medium effect, the guided-mode extracted integral equation and the surface plasmon gap waveguide.

key words: idea, general relativity, electromagnetic theory, integral equations, surface plasmon polariton

1. Introduction

“How to get the original ideas in the research” is the fundamental and critical issue for the researchers in science and technology. The existence of an original idea in the manuscript is the basic criterion for the reviewers. The publication of the papers based on the original idea greatly affects the researcher’s career and is an important step towards increasing carrier. In this paper, I write my experiences of how to get the original idea of three cases, i.e., accelerating medium effect, guided-mode extracted integral equation (GMEIE) and surface plasmon polariton gap waveguide (SPGW) in the research of electromagnetic theory. Publications of these ideas greatly impacted on my career. I would be happy if my experience inspires the spirit of young researchers in electromagnetic theory.

2. Reflection and Transmission of Electromagnetic Waves by an Accelerated Dielectric Slab

In the 1970s, when I was a Ph.D. student in a laboratory of the Osaka University in Japan, many colleagues in the laboratory published papers that treated the scattering of electromagnetic waves by the moving medium or objects with constant velocity. The problems in this subject can be solved by combining Maxwell’s equations with special theory of relativity. Since how to solve these kinds of problems was obvious, I was bored immediately. I wanted to treat the problem which no one knew how to solve.

I was gradually interested in the problems extended to the case of accelerated motion. I realized that the most basic and simplest scattering problem in this subject was not solved. Namely, no one solved the reflection and transmis-

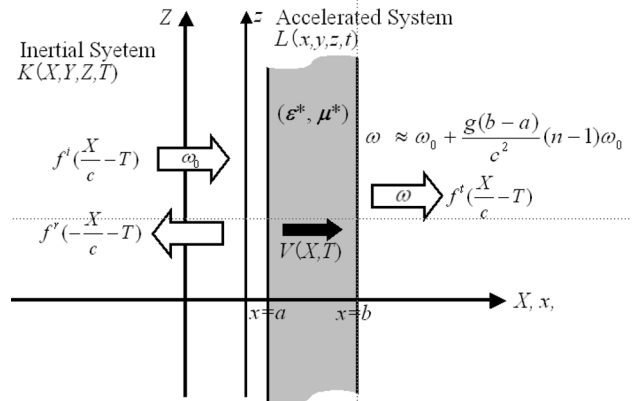


Fig. 1 Reflection and transmission of electromagnetic waves by a linearly accelerated dielectric slab. The dielectric slab performs accelerated motion in the inertial system K . The dielectric slab is at rest in the accelerated system L . The relative permittivity and relative permeability of the slab are given by ϵ^* and μ^* , respectively. The angular frequency ω of the transmitted wave depends on the acceleration g , slab thickness $b-a$ and index of refraction n of the slab, where ω_0 is the angular frequency of the incident wave.

sion of electromagnetic waves by a linearly accelerated dielectric slab (refraction of index n) at normal incidence (one-dimensional problem) shown in Fig. 1. In this problem, we must employ the general relativistic consideration in solving Maxwell’s equations. Since the slab thickness depend on the velocity according to the Lorentz contraction in special relativity in the observer’s inertial system $K(X, Y, Z, T)$, the velocity of the slab $V(X, T)$ depends on both time and position in the system K . So, the problem is not simple and it does not seem to be analytically solvable.

First, we assume that electric fields have only Y component and express the incident, reflected and transmitted fields as:

$$E^i(X, T) = f^i\left(\frac{X}{c} - T\right), \quad (1)$$

$$E^r(X, T) = f^r\left(-\frac{X}{c} - T\right), \quad (2)$$

$$E^t(X, T) = f^t\left(\frac{X}{c} - T\right), \quad (3)$$

respectively in the inertial system K shown in Fig. 1, where $f^i(x)$, $f^r(x)$ and $f^t(x)$ are arbitrary function and c is the light velocity in a vacuum. In order to define the accelerated coordinates system $L(x, y, z, t)$ where the dielectric slab is stationary, we adopt the following coordinates transformations

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proposed by Møller [1]:

$$\begin{aligned} X &= \frac{c^2}{g} \left[\cosh\left(\frac{gt}{c}\right) - 1 \right] + x \cosh\left(\frac{gt}{c}\right), \\ T &= \frac{c}{g} \left[\sinh\left(\frac{gt}{c}\right) - 1 \right] + \frac{x}{c} \sinh\left(\frac{gt}{c}\right), \end{aligned} \quad (4)$$

where $Y = y$ and $Z = z$. The transformations (4) become Newton's transformations as

$$X = x + \frac{1}{2}gt^2, \quad T = t, \quad (5)$$

for the case of small acceleration as $gt \ll c$. So, g is the acceleration of the origin of the system L in the system K . The line element in the system L can be obtained by

$$ds^2 = dx^2 + dy^2 + dz^2 - \left(1 + \frac{gx}{c^2}\right)^2 c^2 dt^2, \quad (6)$$

and the accelerated system L is equivalent to the simple one-dimensional gravitational field. From the general relativistic consideration, Maxwell's equations in the accelerated (gravitational) system L can be written in the same vector form as those in the inertial system K as [1]:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}. \quad (7)$$

Constitutive relations in the accelerated system L are different from those in inertial system and they can be written as

$$\mathbf{D} = \varepsilon_0 \varepsilon^* \left(1 + \frac{gx}{c^2}\right)^{-1} \mathbf{E}, \quad \mathbf{B} = \mu_0 \mu^* \left(1 + \frac{gx}{c^2}\right)^{-1} \mathbf{H}, \quad (8)$$

where $\varepsilon_0 \varepsilon^*$ and $\mu_0 \mu^*$ are permittivity and permeability of the slab, respectively. The electromagnetic wave propagation in the gravitational system L is formally the same as that in the inhomogeneous medium whose constitutive equations are given by (8) in the inertial system. In order to solve the problem in Fig. 1, we must obtain the rigorous solutions of (7) and (8). My idea obtained at that time was as follows:

Idea (From special to general relativities): We first transform plane wave (1) in a vacuum in the inertial system K to that in the accelerated system L according to the rules in general relativity [1]. The solution obtained in this way in a vacuum satisfy the Maxwell Eq. (7) and constitutive relations where $\varepsilon^* = \mu^* = 1$ ($n=1$) in (8) because covariant properties of Maxwell's equations under arbitrary coordinate transformations. The solution in the dielectric in the system L may be similar to that in a vacuum?

I could find that the transformed solution from (1) where t is replaced by t/n satisfy the equations (7) and (8) in the system L . Concrete expressions of electric and magnetic fields are written as [2]:

$$\begin{aligned} E(x, t) &= \frac{1}{n} \left(1 + \frac{gx}{c^2}\right) e^{-\left(\frac{gt}{cn}\right)} f_1 \left[\frac{c}{g} \left(1 + \frac{gx}{c^2}\right) e^{-\left(\frac{gt}{cn}\right)} - \frac{c}{g} \right] \\ H(x, t) &= \sqrt{\frac{\varepsilon_0}{\mu_0 \mu^*}} \frac{1}{n} \left(1 + \frac{gx}{c^2}\right) e^{-\left(\frac{gt}{cn}\right)} f_1 \left[\frac{c}{g} \left(1 + \frac{gx}{c^2}\right) e^{-\left(\frac{gt}{cn}\right)} - \frac{c}{g} \right], \end{aligned} \quad (9)$$

where $n = (\varepsilon^* \mu^*)^{1/2}$ and $f_1(x)$ is arbitrary function and the magnetic field $H(x, t)$ has only z component. The solutions (9) reduce to

$$\begin{aligned} E(x, t) &= \frac{1}{n} f_1 \left(\frac{x}{c} - \frac{t}{n} \right) \\ H(x, t) &= \sqrt{\frac{\varepsilon_0}{\mu_0 \mu^*}} \frac{1}{n} f_1 \left(\frac{x}{c} - \frac{t}{n} \right) \end{aligned} \quad (10)$$

for the case of $g=0$. So, the solution (9) presents a plane wave which propagates to the positive x -direction in the system L . Similarly, the solution which propagates to the negative x -direction in the system L can be obtained from (2). Since two independent solutions in the dielectric slab can be derived, we can introduce boundary conditions on the two surfaces at $x = a$ and b of the slab in the system L . Using the arbitrariness of the function $f_1(x)$ and multiple reflection inside the dielectric, the functions $f^i(x)$ and $f^t(x)$ can be expressed in terms of $f^i(x)$ [2]. Interestingly, there exists the rigorous and analytical solution of the rather complicated problem shown in Fig. 1. From the results obtained, I found an interesting Doppler shift in the frequency of the transmitted wave. The approximate expression of the angular frequency of the transmitted wave ω can be written as

$$\omega \approx \omega_0 + \frac{g(b-a)}{c^2} (n-1) \omega_0 \quad (11)$$

for the case of small acceleration $gt \ll c$, where ω_0 is the incident angular frequency in the system K . The frequency shift (11) depends on the acceleration g , slab thickness $b-a$, index of refraction n of the slab and is independent of the velocity of the slab $V(X, T)$. This Doppler shift can be explained by the drag effect of the dielectric medium [2]. Unfortunately, the frequency shift is very small, i.e., $(\omega - \omega_0)/\omega_0 \approx 10^{-14}$ under reasonable experimental conditions and has not been experimentally verified until now.

Within my knowledge, the result (11) is the only macroscopic electromagnetic phenomenon discovered so far which contains the acceleration of the medium. So, the problem is one of the canonical problems of classical electromagnetic theory which can be solved analytically. Only a small number of researchers were interested in the general relativistic electromagnetic theory at that time, because it was not popular in the scientific community. I could not evaluate my results and did not pursue this subject since then. Recently, A. I. Frank et al. reported experimental work that the neutron transmitted through the accelerated object changes its energy and this phenomenon is same as that of (11) for the case of electromagnetic waves [3]. They call this phenomenon "accelerating medium effect" and show that it is one of the general phenomena in wave phenomena. Furthermore, general relativistic electromagnetic theory has been used in the problem of invisible cloak that is a topic in the field of metamaterials [4]. These results mean that the general relativistic electromagnetic theory was not no prospective theme. In the subject which is not so interested among the researchers, we may have a chance of getting fundamental and original idea due to fewer competitors

from my experience.

3. Guided-mode Extracted Integral Equations

In the 1980s, the low cost PC appeared in the commercial market. I was excited to be able to employ the computer personally in the laboratory instead of main frame in the computer center.

I decided to investigate the subject of simulations of the electromagnetic theory by PC. Since I had an experience of the analysis by integral equation (IE) with moment-method (MoM) previously, I was interested in the problems of dielectric-waveguide discontinuity problems by IE. Especially, the analysis of the dielectric-waveguide bend is the typical problem and it was rather difficult to solve accurately even by the numerical method at that time.

We consider the bend structure of two-dimensional (2D) dielectric slab waveguides shown in Fig. 2. Dielectric waveguide 1 and 2, whose index of refraction is n , are jointed together to form a bend angle (see Fig. 2) $\pi - (\theta_2 - \theta_1)$ though the arbitrary-shaped bend section in the free space. We assume that both waveguides satisfy the single-mode condition and consider the case of TE mode where the electric field $E(\mathbf{x})$ has only z component in the coordinates system in Fig. 2. A TE dominant mode is incident from waveguide 2 to the arbitrary-shaped bend section and the incident wave is reflected, transmitted and scattered by the bend section.

We first consider appropriate virtual boundaries B_1 and B_2 in the waveguide 1 and 2, respectively, shown in Fig. 2. When the virtual boundaries B_1 and B_2 are placed at positions sufficiently far away from the bend section, we can consider that only guided modes exist in the both waveguides over B_1 and B_2 away from the bend section. We denote the boundary of waveguide 2 to B_2 + that of the arbitrary-shaped bend section + that of waveguide 1 to B_1 by C shown in Fig. 2. The infinitely long boundary of the waveguide 1 over B_1 and that of waveguide 2 over B_2 are denoted by C_1 and by C_2 , respectively, shown in Fig. 2. We start from the boundary integral representation of $E(\mathbf{x})$ expressed as

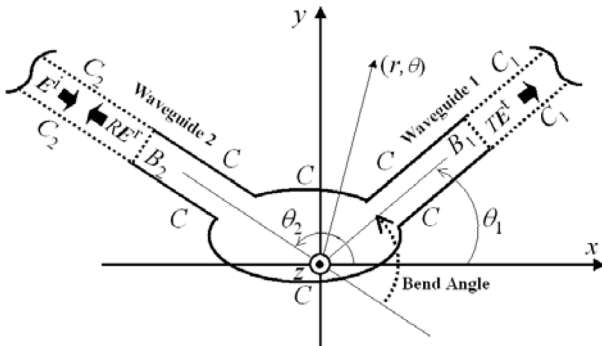


Fig. 2 Dielectric waveguide 1 and 2 are jointed together to form a bend angle $\pi - (\theta_2 - \theta_1)$ though the arbitrary shaped bend section.

$$E(\mathbf{x}) = \int_{C+C_1+C_2} \left[G(\mathbf{x}|\mathbf{x}') \frac{\partial E(\mathbf{x}')}{\partial n'} - E(\mathbf{x}') \frac{\partial G(\mathbf{x}|\mathbf{x}')}{\partial n'} \right] dl', \quad (12)$$

where observation point \mathbf{x} exists inside the dielectric of the waveguide bend, $G(\mathbf{x}|\mathbf{x}')$ is 2D free space Green's function with index of refraction n . It is unrealistic to use the integral representation (12) in the numerical analysis because the boundaries C_1 and C_2 have infinite-length. Using above mentioned consideration, we assume the following conditions:

$$\begin{aligned} \text{Waveguide 1: } E(\mathbf{x}) &= TE^t(\mathbf{x}) \text{ on } C_1 \\ \text{Waveguide 2: } E(\mathbf{x}) &= E^i(\mathbf{x}) + RE^r(\mathbf{x}) \text{ on } C_2, \end{aligned} \quad (13)$$

where $E^i(\mathbf{x})$, $E^r(\mathbf{x})$ and $E^t(\mathbf{x})$ denote the incident, reflected and transmitted guided modes, respectively, and R and T denote the reflected and transmission coefficients, respectively. Substituting (13) into (12) and using Green's theorem, the boundary integrals of the guided modes along the infinitely long boundaries C_1 and C_2 can be changed to those defined by the functions $U^j(\mathbf{x})$ those are boundary integrals along the virtual boundaries B_1 and B_2 of finite-length as follows:

$$\begin{aligned} E^j(\mathbf{x}) - \int_{C_1 \text{ or } C_2} \left[G(\mathbf{x}|\mathbf{x}') \frac{\partial E^j(\mathbf{x}')}{\partial n'} - E^j(\mathbf{x}') \frac{\partial G(\mathbf{x}|\mathbf{x}')}{\partial n'} \right] dl' \\ = U^j(\mathbf{x}) \\ = \int_{B_1 \text{ or } B_2} \left[G(\mathbf{x}|\mathbf{x}') \frac{\partial E^j(\mathbf{x}')}{\partial n'} - E^j(\mathbf{x}') \frac{\partial G(\mathbf{x}|\mathbf{x}')}{\partial n'} \right] dl', \end{aligned} \quad (14)$$

where superscripts $j = i, r$ and t indicate the incident, reflected and transmitted wave, respectively. From (12) and (14), we can obtain the following representation:

$$\begin{aligned} E(\mathbf{x}) = \int_C \left[G(\mathbf{x}|\mathbf{x}') \frac{\partial E(\mathbf{x}')}{\partial n'} - E(\mathbf{x}') \frac{\partial G(\mathbf{x}|\mathbf{x}')}{\partial n'} \right] dl' \\ - TU^t(\mathbf{x}) - RU^r(\mathbf{x}) - U^i(\mathbf{x}). \end{aligned} \quad (15)$$

We notice that all the boundaries C , B_1 and B_2 in (15) are finite-length. It is possible to apply MoM to the integral equations of finite-length boundaries. However, since two unknown coefficients T and R are included in (15), numerical evaluation by MoM cannot be performed directly.

Inspiration (Fundamental recreations are required):

The reflection and transmission coefficients R and T must be related to $E(\mathbf{x})$ on the boundary C . If there exist simple relations that relate R and T to $E(\mathbf{x})$ on the boundary C , we can delete the unknown constants R and T in (15) and can obtain the integral representation whose unknown is $E(\mathbf{x})$ only on the boundary C .

Fortunately, the simple relation could be found as follows: We first calculate the radiation field inside waveguides by substituting the asymptotic expression of 2D Green's function to (15) as

$$E(r, \theta) = -\frac{j}{4} \sqrt{\frac{2}{\pi n k_0 r}} B(\theta), \quad (16)$$

where r and θ represent cylindrical coordinates shown in

Fig. 2. The expression $B(\theta)$ represents the radiation pattern inside waveguides and expressed as

$$B(\theta) = \int_C \left[g(\theta|\mathbf{x}') \frac{\partial E(\mathbf{x}')}{\partial n'} - E(\mathbf{x}') \frac{\partial g(\theta|\mathbf{x}')}{\partial n'} \right] dl' - Tu^t(\theta) - Ru^r(\theta) - u^i(\theta), \quad (17)$$

where

$$u^j(\theta) = \int_{B_1 \text{ or } B_2} \left[g(\theta|\mathbf{x}') \frac{\partial E^j(\mathbf{x}')}{\partial n'} - E^j(\mathbf{x}') \frac{\partial g(\theta|\mathbf{x}')}{\partial n'} \right] dl', \quad (18)$$

$$g(\theta|\mathbf{x}') = \exp(jnk_0 x' \cos \theta + jnk_0 y' \sin \theta), \quad (19)$$

where $j = i, r$ and t . Since only guided modes exist in the waveguides 1 and 2 at points far away from the bend section, we must put as

$$B(\theta_1) = 0 \text{ and } B(\theta_2) = 0, \quad (20)$$

from the consistency with the assumption (13). There are two unknown constants R and T in (17) and two relations of these unknowns can be obtained as (20). So, the R and T can be expressed in terms of $E(\mathbf{x})$ only along the boundary C . Substituting resultant expressions of R and T to (15), we finally obtain in the following integral representation as [5]

$$E(\mathbf{x}) = \int_C \left[P(\mathbf{x}|\mathbf{x}') \frac{\partial E(\mathbf{x}')}{\partial n'} - E(\mathbf{x}') \frac{\partial P(\mathbf{x}|\mathbf{x}')}{\partial n'} \right] dl' + S(\mathbf{x}), \quad (21)$$

where

$$P(\mathbf{x}|\mathbf{x}') = G(\mathbf{x}|\mathbf{x}') - [U^t(\mathbf{x})W(x') + U^r(\mathbf{x})V(x')]/\Delta, \quad (22)$$

$$W(x') = u^r(\theta_2)g(\theta_1|\mathbf{x}') - u^t(\theta_1)g(\theta_2|\mathbf{x}'),$$

$$V(x') = u^t(\theta_1)g(\theta_2|\mathbf{x}') - u^r(\theta_2)g(\theta_1|\mathbf{x}'), \quad (23)$$

$$S(\mathbf{x}) = U^r(\mathbf{x}) + \{U^t(\mathbf{x})[u^r(\theta_1)u^t(\theta_2) - u^t(\theta_2)u^r(\theta_1)] + U^r(\mathbf{x})[u^t(\theta_2)u^r(\theta_1) - u^r(\theta_1)u^t(\theta_2)]\}/\Delta, \quad (24)$$

$$\Delta = u^t(\theta_1)u^r(\theta_2) - u^r(\theta_1)u^t(\theta_2). \quad (25)$$

When we use integral representation (12) in solving the waveguide discontinuity problem of infinite-length such as bend problem shown in Fig. 2, we usually employ the mode-expansion technique. In contrast, the integral representation (21), which is derived by introducing specific conditions at points far away from the bend, have boundaries of finite-length by putting virtual boundaries B_1 and B_2 at appropriate points far away from the discontinuity shown in Fig. 2. Furthermore, the basic structure of the representation (21) is very similar to that of the original one (12) apart from the differences in the kernel function $P(\mathbf{x}|\mathbf{x}')$ and in the impressed term $S(\mathbf{x})$. So, the conventional MoM can be applied directly to the boundary integral equations derived from (21) without mode-expansion technique. We have called these integral equations Guided-mode Extracted Integral Equations (GMEIE's) [6]. It is extremely interesting that the waveguide discontinuity problems can be regarded as a kind of the scattering problem of the finite-sized object by GMEIE's. We notice that the coefficients of the guided mode R and T derived from (17) and (20) can be expressed in terms of the asymptotic form of Green's function, i.e.,

far field representation. So far, asymptotic form of Green's function can be used only in the expression of the radiation field. Interestingly, we can regard the coefficient of guided-mode as a part of the radiation pattern. We confirmed that the results obtained by GMEIE's are agree well with those obtained by mode-expansion technique for some problems [7].

The idea used GMEIE's is so simple and so straightforward that we were afraid that similar idea must be already published in the journal. Fortunately, we could find no paper that treats similar idea. Another concern was that the GMEIE (21) was derived under single-mode condition. In general, the waveguide discontinuity problems satisfy the multi-mode conditions. Under these conditions, the number of the unknowns of the guided-modes (reflection and transmission coefficients) can become more than two. However, in the above-mentioned derivation of (21), only two relations (20) can be used. In the problem under multi-mode conditions, apparently, more relations are required in order to determine the unknown coefficients whose number is larger than two. We could conceive the astonishing idea to solve this concern by solving the problem under two-mode condition [6].

We applied GMEIE's to the problems of near-field optics (NFO) which was the popular topics in the field of optics at that time [8]. An example of simulation of SNOM (Scanning Near-field Optical Microscope) is shown in Fig. 3. The dielectric object which is smaller than the wavelength λ is placed on the glass substrate and illuminated by the evanescent fields from inside of the substrate. If the near-field around the object are detected by the optical dielectric probe-tip, the transmitted waves in the probe can make a scanning image of the near-field around the object. Since the near-field distribution does not satisfy the diffraction-limited condition, we can expect that the resolution of the near-field imaging can be larger than the wavelength. How-

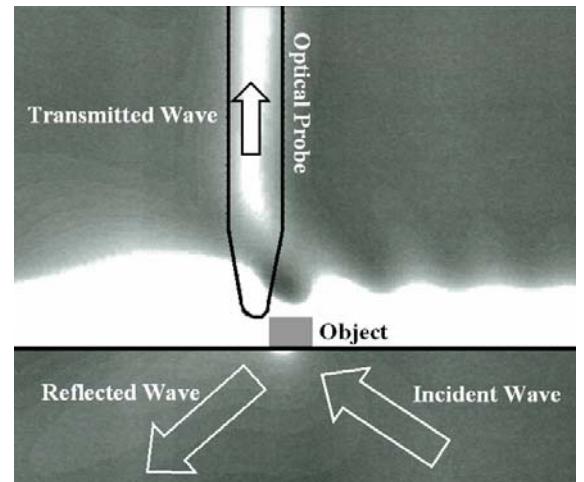


Fig. 3 Example of the simulated optical intensity distribution of SNOM (Scanning Near-field Optical Microscope) by GMEIE's. Relative permittivities of the dielectric substrate, probe and object are 2.25. The size of the object is about $0.16\lambda \times 0.16\lambda$ (λ is the wavelength).

ever, the simulation result by GMEIE's shows that the probe detects not only the near-field around the object but also the field which enters into the probe through side boundary of the probe shown in Fig. 3 in some cases [9]. So the higher resolution is not be easy to realize by the SNOM structure shown in Fig. 3. The idea of GMEIE's is so basic that it can be applied to problems in the wide wave phenomena and we have applied them to the quantum electron waves [10].

The main theme of my research when I was Ph.D. student was general relativistic electromagnetic theory as stated in the previous section. I was not familiar with the integral equation (IE) and MoM first. Fortunately, one senior colleague Dr. N. Morita (Osaka University at that time) who is an expert of IE was sitting in the next desk. Furthermore, another senior colleague Dr. M. Tsutsumi (Osaka University at that time) who is an expert of magnetoelastic waves was working in the next room. We often talked and discussed with each other concerning our own research subjects. So, I could promptly study the know-how of the IE with MoM and complicated magnetoelastic waves without large difficulties. I tried to derive the IE's of magnetoelastic waves. In this process, I could deeply understand Maxwell's theory, IE and complicated magnetoelastic waves and I had an idea of GMEIE's. However, I could not derive the definite result of (21) at that time. Since I eventually moved to Gifu University and engaged in the different research, we could not continue to pursue this idea. However, I sometimes considered this idea during my main work. After ten years later, when I tried to derive GMEIE's, I could come up with the essential results (21) within about one hour. My experience indicates the importance of wide interest in other subjects and intimate relationship with researchers sitting on the next desk or working in the next room. Of course, it is also important to continue to consider the problem for a long time and to continue to consider the problem deeply.

4. Surface Plasmon Polariton Gap Waveguide

In the 2000s, the performance of PC was extremely improved and its price drastically decreased. We could now perform three-dimensional simulations which were rather difficult in the laboratory so far. At that time, in the field of NFO, the near-field in the aperture whose size is much smaller than the wavelength was interested by many researchers. We tried to solve the scattering of optical waves by a rectangular aperture in the thick metallic screen shown in Fig. 4. A small square aperture whose size is given by $a_x \times a_y$ is formed in a metallic and infinite-sized screen with thickness w shown in Fig. 4. A plane wave with wavelength λ is assumed to be incident from the region below the screen. Since the metal is the dielectric medium with complex permittivity $\epsilon_1 \epsilon_0$ in the optical wavelength region, we adopted the volume integral equation (VIE) with MoM in the analysis. Since the screen has infinite-size, we employed similar idea to that used in GMEIE's in order to make the problem finite-sized one, i.e., numerically solvable problem. We discretize the VIE by MoM and employ the iteration tech-

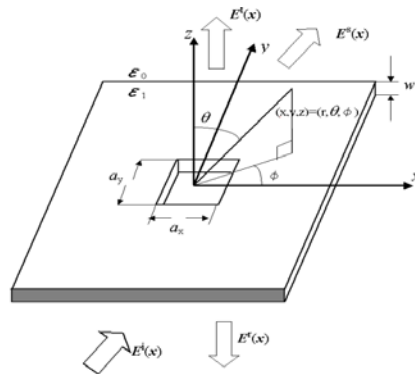


Fig. 4 Scattering of optical waves with wavelength λ by the small square aperture in the thick metallic screen. ($a_x \times a_y = 0.19\lambda \times 0.19\lambda$, $w = 0.3\lambda$, $\epsilon_1/\epsilon_0 = -7.38 - j7.18$)

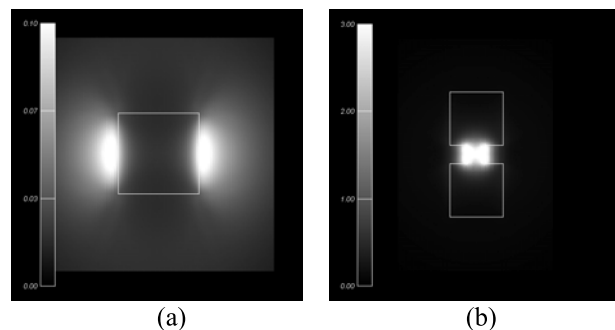


Fig. 5 Optical intensity distributions on the plane which is separated by $d = 0.02\lambda$ (λ is the wavelength) from the screen-surface for (a) square aperture and (b) I-shaped aperture. The size of the upper and lower square is same as that of (a) and the size of narrow gap region is $0.06\lambda \times 0.06\lambda$. Intensity scale-ranges are 0.0-0.1 in (a) and 0.0-3.0 in (b) normalized by the incident intensity. ($a_x = a_y = 0.19\lambda$ and $w = 0.3\lambda$, $\epsilon_1/\epsilon_0 = -7.38 - j7.18$). White lines shown the shapes of the aperture.

nique of generalized minimum residual method (GEMRES) with fast Fourier transformation (FFT) to solve the resultant system of linear equations. This numerical technique is well-known and the orthodox method in the computational electromagnetics. We could obtain the reasonable solution that satisfies optical theorem and reciprocity by this technique [11].

A typical optical intensity distribution just above the square aperture is shown in Fig. 5(a) for the case of $\epsilon_1/\epsilon_0 = -7.38 - j7.18$. The polarization of the incident wave is horizontal direction in Figs. 5 and 6. Since the aperture size and screen thickness are given by about $0.19\lambda \times 0.19\lambda$ and 0.3λ , respectively, we can consider that the aperture is a hole through the thick metallic screen. So, we can use the metallic waveguide theory to understand the characteristics of the results. The rectangular waveguide whose cross section is $0.19\lambda \times 0.19\lambda$ is apparently under cutoff condition. It is reasonable that the optical intensity shown in Fig. 5(a) is much smaller than the incident intensity (Notice that the intensity scale range of Fig. 5(a) is 0-0.1 normalized by the incident intensity). We looked for the shape of the aperture which generates large near-field intensity and small size of

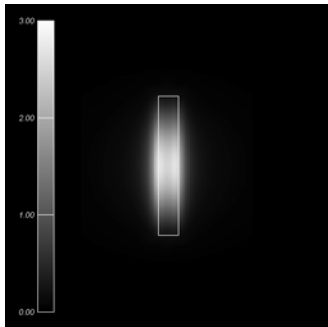


Fig. 6 Optical intensity distributions on a long and narrow rectangular aperture whose size is $a_x \times a_y = 0.06\lambda \times 0.45\lambda$. Intensity scale-range normalized by the incident intensity is 0.0-3.0. ($w = 0.3\lambda$, $\epsilon_r/\epsilon_0 = -7.38 - j7.18$). White lines shown the shapes of the aperture.

the intensity distribution on the aperture, because the aperture having these characteristics will be useful for the optical probe of NFO equipment such as SNOM and optical storage systems. Fortunately, we could find the I-shaped (dumbbell-shaped) aperture can create such a near-field distribution shown in Fig. 5(b) [12]. This aperture is composed of two square apertures connected by a narrow gap region shown in Fig. 5(b). The sizes of two square apertures are same as that shown in Fig. 5(a). We can see that the optical intensity is localized in the narrow gap region and its intensity about three times of the incident intensity in Fig. 5(b). The size of narrow gap region is given about $0.06\lambda \times 0.06\lambda$ which is much smaller than the wavelength.

At first, we were confused by the result of Fig. 5(b), because we could not explain the mechanism of the localization and enhancement of optical field on the narrow-gap region in the I-shaped aperture. We had another confusing result of the optical intensity in a long and narrow rectangular aperture shown in Fig. 6. Since the size of the aperture is given by $a_x \times a_y = 0.06\lambda \times 0.45\lambda$, this aperture (waveguide) satisfies the cutoff condition. However it seems that the optical wave can propagate through the aperture, because near-fields in Fig. 6 is rather large compared with the result shown in Fig. 5(a) under cutoff condition.

The height of rectangular waveguide which gives cutoff condition of TE_{mn} -mode is given by

$$a_y = m\pi / \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - \left(\frac{n\pi}{a_x}\right)^2}. \quad (26)$$

For the simplest case of TE_{10} ($m=1, n=0$), the height a_y becomes 0.5λ . The minus sign inside the square root in the denominator of (26) is due to the assumption that the electric field in the waveguide can be expressed by the trigonometric function along the horizontal axis in Fig. 6. In other word, this minus sign is based on the property that the sign of trigonometric function is reversed by two-times differentiation. If this sign can be plus and $n \neq 0$ in (26), the height which gives the cutoff condition can be decreased and the waveguide of $a_y = 0.45\lambda$ may escape from the cutoff condition. We notice that if the field distributes according to the

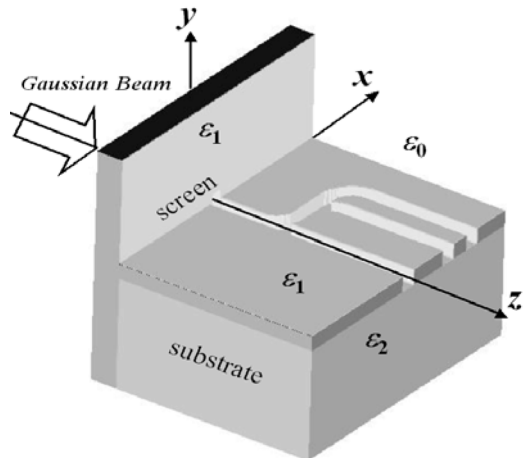


Fig. 7 Four ports branching SPGW circuit fabricated on the dielectric substrate. The relative permittivities of the metal and dielectric substrate are given by $\epsilon_1/\epsilon_0 = -7.38 - j1.03$ and $\epsilon_2/\epsilon_0 = 2.25$, respectively, with wavelength $\lambda = 633$ nm.

exponential function along the horizontal axis in the aperture, this sign become plus because the sign of exponential function is not reversed by two-times differentiation. This means that the optical wave which propagates in the metallic aperture (hole) is a surface wave, i.e.,

Hint (Fundamental wave on the metal surface): Surface Plasmon Polariton (SPP).

Since the phase velocity of SPP in the small gap region is smaller than that in the wide gap region (in the square apertures) in Fig. 5(b), SPP is localized in the narrow gap region shown in Fig. 5(b). This result indicates that it is possible to guide SPP (optical wave) along the small gap region whose cross-section is much smaller than the wavelength. We immediately noticed that this result can be applied to the construction of the optical waveguide circuits, composed of gap structure in the metal whose size is smaller than the wavelength. For example, the thin metal (Au) is placed on the dielectric substrate and four port branching waveguide is fabricated by the gap in the thin metal shown in Fig. 7. The Gaussian beam is assumed to be incident into this circuit through the small hole in the screen. The scattering problem in Fig. 7 was solved by the simulation code based on VIE and GMRES with FFT. The resultant optical intensity distribution in the circuit is shown in Fig. 8. The whole size of the circuit can be compared with an arrow of one wavelength in Fig. 8(a). This result shows that it is possible to construct practical nanometric optical circuits by using SPP that propagates along the gap structure in the thin metal. We called this waveguide surface plasmon polariton gap waveguide (SPGW). We are proud to the papers of SPGW published in 2003 and 2005 as the pioneering works of nanometric optical waveguide circuits. These papers have been referred by many authors [13], [14].

The mechanism of SPGW is very simple. It was puzzling for us that no one reported the application of this

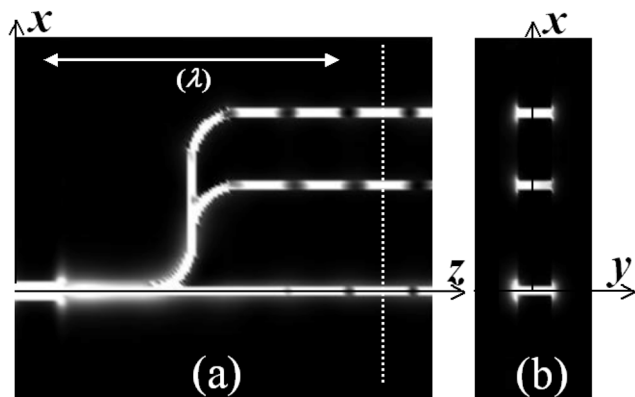


Fig. 8 Optical intensity distributions (a) on the x - z plane and (b) on the plane parallel to the x - y plane placed on the position of the dotted line in (a) of four ports branched SPGW circuit in Fig. 7. The intensity scale is 0.0–4.0 normalized by the incident intensity. The cross section of SPGW (gap in the metal) is $0.06\lambda \times 0.16\lambda$.

mechanism to nanometric optical circuits before our publication. The reason why we could conceive the SPGW first is the construction of hand-made simulation code which can treat SPP problems before anyone else in the field of NFO. Hand-made code is easy to use and the convenient commercial codes which can treat the SPP problems effectively was not available at that time. The simulation code based on VIE + MoM + GMRES + FFT is well-known and orthodox technique in the field of the computational electromagnetics. However, this technique is a little cumbersome and is not popular in the field of NFO. So, even if a researcher of NFO was aware of the mechanism of SPGW, he might be unable to publish the results due to the lack of simulation code. We were ahead than anyone in the simulation of SPP at that time. Our experience of research of SPGW indicates the importance of the simulation code in the research of electromagnetic theory in recent years.

5. Conclusions

From our research experience of three subjects, the following results have been obtained about the issue “How to get the original ideas in the research”:

- When we choose the subject that only a small number of researchers is interested in because it is not popular, we may have a chance of getting original idea because of fewer competitors. However, there is a risk to pursue a career.
- We should be interested in the subjects of the researchers sitting on the next desk or working in the next room. We can easily understand the know-how of their subjects by intimate contact. Combining these subjects with own knowledge, we often come up with the interesting original idea.
- Interesting inventions or discoveries in the electromagnetic theory in the future will be done by the simulation code, not by paper and pencil. Therefore we should always maintain, develop and improve the simulation code.

I would like to write an impressive saying which I saw in U.S. as follows:

“Words that discourage young people most are ‘Your idea is that someone has already come up with’. It was not the case. Many ideas were the first. Young people should open up own life with the confidence in their own idea.”
I was often encouraged by this saying.

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