Metal-Slit Array Fresnel-Lens for Optical Coupling

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***Abstract-* We proposed, for the first time, to utilize metal-slits array *Fresnel* lens for the optical coupling form free space into silicon slab waveguide while overcoming near focal length limit of the conventional dielectric *Fresnel* lens. Physical limits of the conventional *Fresnel* lens were revealed and it was proposed to employ metal-slit array to overcome these limitations. Comparative study has been carried out with a FDTD simulation between normal *Fresnel* lens coupling and metal-slit array *Fresnel* lens coupling.**

I. INTRODUCTION

Recently, much research has been done for realizing nano-scale photonic circuits based on photonic crystal, plasmonics and silicon photonics in order to overcome fundamental limits of electronic circuits such as bottleneck of speed increasing and size reduction. However, reduction of the circuit size seems meaningless when a structure for the light coupling from optical fiber into the nano-scale circuit is even larger than the circuit itself. One of the possible solutions to reduce coupling length is utilizing micro lens while shortening the focal length of the micro lens as sort as possible. In such a case, solid immersion lens concept should be used to reduce spot size [1] (the spot size cannot be reduced enough in the free space when injection into high refractive index material is required). Also, additional reducing of coupling length can be achieved by making its lens as Fresnel lens. However interesting point is that making *Fresnel* lens which takes ultra-short focal length actually causes a problem when immersion material is used to reduce spot size because light propagation is blocked by *Fresnel* lens structure itself. On the other hands, there has been an explosion of interest on the manipulation of the light utilizing the unique property of plasmonic wave beyond diffraction limits since the extraordinary transmission through sub-wavelength hole had been reported [2].

In this research, we showed that how the limitation on the shortening of coupling length with the conventional dielectric lens could be solved by using metal-slit array lens so that coupling length is drastically reduced by the unique natures of the plasmonic wave. With the comparison between conventional dielectric lens and metal-slit array-lens appropriate coupling structure were suggested and detail design principles were described.

II. THEORY

The structure of the silicon *Fresnel* lens we would like to study is shown in the Fig. 1 (*a*). This structure is designed that beam taking spot size of around 10 μm in the free space can be coupled into 0.36 μm thick silicon slab waveguide by the coupler. The *Fresnel* lens has a focal length of 1.5 μm and silicon is located as an immersion material between the lens and the waveguide (all of the structure is made of silicon). When observing the cross sectional view of the light path through this coupler, it can be observed that a problem is caused by shortening the focal length. As can be seen in this figure, the actual optical path (solid line) of the light does not match with the intended light path (dotted line: designed to be focused on the entrance of slab waveguide). The light which is refracted at the entrance-surface of the *Fresnel* lens is reflected by the structure itself when the light reaches the free space while silicon-air interface is causing total internal reflection.

To overcome this problem, this research proposes to utilize metal-slits array-lens instead of pure silicon lens as shown in the Fig. 1 (*b*). This configuration does not cause light path problems as shown in the Fig. 1 (*b*) because the light is refracted at the emitting-surface of the lens after light is guided straight toward the end of the lens by the surface plasmon waveguide that is made of metal slits.

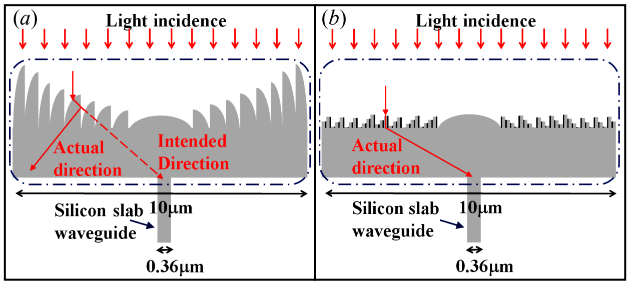

Figure 1. (*a*) Structure of the silicon *Fresnel*-lens coupler. (*b*) Structure of the Metal-slit assisted *Fresnel*-lens coupler. Propagation paths of the light are shown and dotted line is the intended path and solid line is actual path of the input light.

It is well-known that the surface plasmon can be utilized for beam manipulations such as focusing [3] or beaming direction control [4]. The principle of these phenomena is same with the phased array antenna concept in the fields of antenna theory. With appropriate design, wave can be focused on entrance of the silicon slab wave guide so that the wave that has a large spot size can be coupled into silicon slab waveguide. Fig. 2 shows the design parameters of the metal-slit assisted *Fresnel*-lens coupler.

The first step is to determine l_0 referring to Fig. 2. At that time, l_0 must be as long as possible in order to extend width of

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the pure silicon region as far as circumstances permit. Namely, width of the plasmon waveguide region must be as narrow as possible because surface plasmon waveguide has some attenuation. So, the l_0 can be set as the longest length of the surface plasmon waveguide which will be designed later (If the l_0 is longer than the longest length of the surface plasmon waveguide working distance is extended by the reasons of the l_0). And, the longest length of the plasmon waveguide can be calculated from the condition satisfying that propagation length makes phase difference of one period between free space and plasmon waveguide ($l_0 = \mathrm{Max}\{l_p\} = 2\pi/(\beta_3-\beta_1)$). And then, lengths of l_s and l_p can be determined from the phase matching condition of the (1).

$$\beta_2(l_0+l_f) = \beta_1(l_0-l_s) + \beta_2\sqrt{(l_s+l_f)^2+d_s^2} + 2\pi\cdot M$$
$$= \beta_1(l_0-l_p) + \beta_3 l_p + \beta_2\sqrt{l_f^{\,2}+d_p^2} + 2\pi\cdot N \qquad (1)$$

Where, l_f, l_0, l_s, and l_p are the focal length from the emitting-surface of the lens, length at the center of the silicon lens, length of the silicon lens and length of the plasmonic waveguide respectively. And, M and N are integer, d_s and d_p are distance from the center, and, β_1, β_2, β_3 are the propagation of free space, silicon, plasmonic waveguide respectively. Each elemental surface plasmon waveguide can be considered as MIM (Metal-Insulator-Metal) structure, which of course means that width of the metal layer (w_m) is wide enough compared with skin depth so that there is not any interaction between adjacent waveguides. In such a case, propagation constant (β_3) of the plasmonic wave in the MIM structure can be calculated [3] using (2).

$$\tanh\left(\sqrt{\beta_3^2-k_0^2\varepsilon_d}\,w_d/2\right) = \frac{-\varepsilon_d\sqrt{\beta_3^2-k_0^2\varepsilon_m}}{\varepsilon_m\sqrt{\beta_3^2-k_0^2\varepsilon_d}} \qquad (2)$$

Where, k_0 is the wave vector in the free space, ε_d and ε_m is relative permittivity for the insulator and metal, w_d is the width of the insulator between metal layers. In our design, gold (ε_m = -140 + 10*i* at 1550*nm* [5]) and silicon ($\varepsilon_m = 3.5^2$) are used as a metal and an insulator.

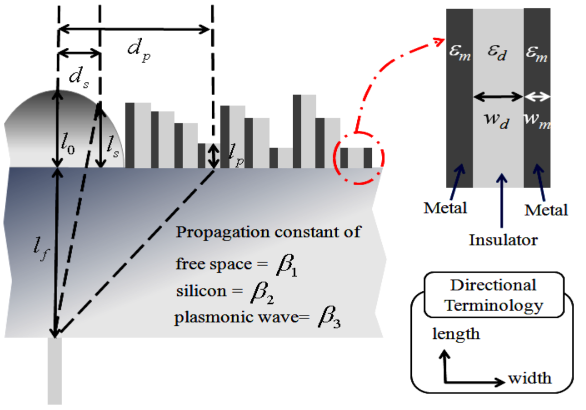

Figure 2. Design parameters of the metal-slit assisted *Fresnel*-lens coupler and extended view of elemental surface plasmon wave guide.

III. RESULTS

2D-FDTD calculation was carried out with 5 nm grid size for the coupling structure which is designed with above described design principles. *Gaussian* input beam with 10 µm spot size was applied from the free space into designed coupler and the focal length of the *Fresnel* lens was set as 1.5 µm (1.5 µm is the shortest focal length because if the focal length is shorter than around 1.5 µm, incidence angle exceeds acceptable angle that is restricted by the numerical aperture of the silicon slab waveguide). Fig. 3 shows the FDTD calculation results of the designed coupling structures (w_d = 100 nm, w_m = 50 nm). In the case of (*b*) which is proposed by this paper total working distance is just around 2 µm while working distance of (*a*) is around 4 µm. Fig. 5 (*c*) and (*d*) show *Poynting* vectors for the structures of (*a*) and (*b*) respectively when the powers are normalized to 1. As expected, diverging light by the total internal reflection can be seen in the case of the (*c*). Coupling efficiencies of around 32% and 50% were measured for Fig. 5 (*c*) and (*d*).

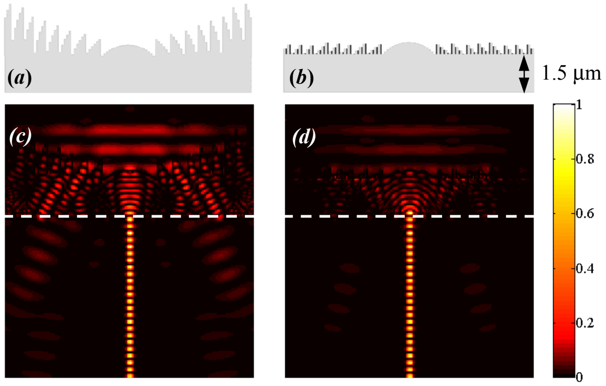

Figure 3. Comparisons between normal *Fresnel* lens coupling and metal-slit array *Fresnel* lens coupling. (*a*) Scaled coupling structure of the normal *Fresnel* lens. (*b*) Scaled coupling structure of the metal-slit array *Fresnel* lens. (*c*) Normalized *Poynting* vector plot for the normal coupling. *(d)* Normalized *Poynting* vector plot for metal-slit assisted *Fresnel* lens coupling that takes silicon width of 100 nm and metal width of 50nm.

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