Gain Enhancement of Optical Leaky wave Antenna Excited by Parabolic reflector with Photonic crystal

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Abstract: This paper presents gain enhancement of leaky wave antenna by parabolic reflector of photonic crystal. A leaky wave antenna has been proposed as an antenna for optical wireless communication. This antenna is excited by a parabolic reflector made of photonic crystals. This excitation method is very compact, resulting in some insertion loss. To improve the drawback, we propose a new reflector combined by photonic crystals and glass layer.

Keywords: Leaky wave antenna, parabolic reflector, photonic crystal.

Classification: Antennas and propagation

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1 Introduction

In recent years, data traffic has been increasing due to the rise in the number of smartphones, tablets, and other communication devices. Therefore, optical wireless communication has received significant attention to develop the frequency resources. The size of the antenna is inversely proportional to the frequency and antennas for optical wireless communication are fabricated by silicon photonics processes. Leaky wave antennas made by this process have been proposed as antennas for optical communications. The conventional excitation method is a taper waveguide and a parabolic reflector has been proposed as a compact excitation method[1]. In this paper, we clarify the cause of insertion loss in parabolic reflectors and propose a method to improve it.

2 Structure and simulation

Fig. 1 shows the geometry of optical leaky wave antenna excited by parabolic reflector. The antenna is fabricated from a silicon substrate with a thickness of 0.21µm, sandwiched between clad of silica. The refractive index of silicon is 3.45 and that of silica is 1.45. The range of wavelength is from 1.50µm to 1.60µm (from 187THz to 200THz). The antenna is a grating waveguide (GWG)[2], one of the optical leaky wave antennas with very simple structure. The GWG has linear periodic grooves on the surface of the waveguide and a single period is defined as \( A_{GWG} \). The entire waveguide length \( L_{GWG} \) is then expressed as \( N \times A_{GWG} \), where \( N \) is the number of periods. To excite antenna, the light in a silicon waveguide with a width of 0.45µm need to be converted into a plane wave with a wider width. The parabolic reflector can convert light from a silicon waveguide into a plane wave. The low loss material of the reflector is gold, however, it is difficult to create the gold reflector by silicon photonics. Then the photonic crystals (PC) in a parabolic pattern as shown in Fig. 1(c) was proposed[1]. The PC is a periodic array of circular holes to reflect light at a specific wavelength[3,4]. The parabolic reflector is a very compact excitation method compared to the conventional tapered waveguide.

We attached a slab waveguide of 28.5µm width and 20µm length to the reflector and evaluate S21 parameter and its electric field distribution. We use CST MW Studio suite 2020[5]. The S21 in Fig. 1(d) shows the power transmission from the Si waveguide to the slab waveguide. We also show the results of the gold reflector as a comparison. Over all the range of wavelengths, the S21 parameter is lower than gold reflector, which indicates that the reflector of PC has some loss. Fig. 1(e) shows the electric field distribution of the PC reflector. A part of the plane wave inputted into the slab waveguide is scattered to the undesirable reflection, resulting in the insertion loss.
To find the reason of the loss as shown in the previous section, we discuss the undesirable reflection of the PC characteristics. For example, when light is incident on flat gold reflector, it reflects light in only one direction, satisfying the law of reflection. The material used for the parabolic reflector must satisfy the law of reflection. Fig. 2(a) shows the electric field distribution for the plane wave incidence on the PC from port1 with the incidence angles of 25°. We find the reflections in two directions. One is the direction by the law of reflection, and the another is different direction, causing the undesirable
reflection in Fig. 1(e). When the incident angle is $15^\circ$, the reflection satisfying the law of reflection is about 80%, while it decreases to 50% at $30^\circ$, and 20% at $45^\circ$. Reflection divided in two angles are caused by the geometry of the photonic band gap (PBG). The PBG prohibits the propagation of a specific range of wavelengths as shown in Fig. 2(b). The unit lattice of PC used in the reflector is a hexagonal lattice, generating reflections in the directions $\Gamma$ to $M$ and $\Gamma$ to $K$. The angles difference between $\Gamma$-$M$ and $\Gamma$-$K$ is $30^\circ$. The $\Gamma$-$M$ direction satisfies the law of reflection, while $\Gamma$-$M$ direction causes another directed reflection.

**Fig. 2.** Directed reflection structure and electrical field of PC

\[ \theta_i = 25^\circ \]

(a) Electric field distribution of PC  
(b) Direction of PBG

\[ 2r_{PBG} \]

(c) Schematic of combination of PC and Glass layer  
(d) Electric field distribution of combination of PC and Glass layer

\[ t = 110[\text{nm}], r_{PBG} = 110[\text{nm}] \]

\[ d = 300[\text{nm}], A_{PBG} = 410[\text{nm}] \]

(e) Principle of reflection

$\theta_i$: the incident angle $\theta_f$: the reflection angle

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We proposed a new structure to suppress the unwanted reflection by inserting a thin glass layer in front of the PC as shown in Fig. 2(c). When the incident angle is 25°, the reflection in another direction is not observed as shown in Fig. 2(d). When the incident angle is 15°, the reflection satisfying the law of reflection is about 90%, but it decreases to 80% at 30°, and 60% at 45°.

The reflectivity of the glass layer increases with the angle of incidence. Fig. 2(e) shows the principle of reflection. The angle of reflection in the another direction is larger than the incident angle. Therefore, the reflection satisfying the law of reflection pass through the glass layer. On the other hand, the reflections in another directions are reflected by the glass layer. It excites evanescent mode and cannot propagate between the PC and the glass layer. The scattered light cancels each other out, while the reflected light satisfying the law of reflection is summed up. As a result, the plane wave exciting the leaky waveguide increases.

Therefore, this new structure combining a glass layer and PC can prevent reflection in another direction and increase the antenna gain.

4 Simulation of parabolic reflector combining glass layers and photonic crystals

The proposed structure is applied to the leaky antenna. Fig. 3(a) shows the schematic diagram and the parameters. The S21 parameters are also shown in Fig. 3(b). As a comparison, the results of the conventional reflector and the gold reflector are shown. The reflection into the slab waveguide is greater than that of the conventional parabolic reflector in all wavelength bands and the reflection is almost equal to that of the gold reflector at the central wavelength. Fig. 3(c) also shows the electric field distribution. The undesirable reflection has been greatly reduced. We also connected a grating waveguide to the reflector and compared the gain, where $A_{GWG}$ is 570nm, the groove depth is 70nm, and the period number N is 30. Compared to the conventional reflector, gain increase by 1.1dBi to 1.3dBi is observed in the range of 1.53$\mu$m to 1.59$\mu$m. At other wavelengths, it is from 0.6dBi to 1.0dBi.

5 Conclusion

In this paper, we first clarified that the loss in of parabolic reflector is caused by the reflection characteristics of the photonic crystal. Then we proposed a new structure combining the photonic crystal and the glass layer. As a result, we showed that it prevents undesirable reflection and increases the amount of reflection and gain.

6 Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP18K04218.
Fig. 3. Structure and electrical field of PC