

Design of Nano-Photonic Phased-Array Antennas for Wide-Angle Beam-Steering

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Abstract— We propose nano-photonic phased-array antennas suitable for wide-angle beam-steering. Two types of the antennas are designed based on the grating structure and the plasmonic metal thin film, and their radiation performances are simulated using a finite-difference-time-domain simulator. From both antenna arrays with narrow array pitches near the wavelength scale, we show a possibility of wide beam-steering over 90° in the lateral direction.

Keywords— Phased-array antenna, optical radiator, grating radiator, metallic nano-antenna, photonic antenna

I. INTRODUCTION

The photonic phased-array antenna has been received attractions as the light source for image scanning and communication with LiDAR (light detection and ranging) systems, especially, for the applications to manless vehicles, robots, measuring instruments etc. For these applications, the nano-photonics based antenna can provide peculiar advantages in compactness, low power consumption and high-speed scanning.

Recently, large-scale two-dimensional (2D) nano-photonic phased-array [1] was demonstrated with nano-grating antenna fabricated by the CMOS-compatible silicon photonic technology. In this 2D array, most of such antenna elements as coupler, phase delay line and grating antenna are configured in the unit pixel, and thus the space is restricted in the design of the grating antenna. For an efficient radiation the periods of the grating should be increased, but for a wide beam-steering the pitch of the pixel should be reduced as possible. Both of these requirements could not be satisfied together in the 2D array in which many elements are integrated in each pixel. For an efficient and a wide beam-steering, 1D array could be more proper since the grating antenna can be compactly configured in the lateral direction to provide a wider steering performance and the grating period can be freely extended in the longitudinal direction to attain an efficient radiation. Such 1D phased-array was demonstrated with silicon nano-photonics [2]. In this work, a solution for the beam-forming in the longitudinal direction was also proposed by using tunable wavelengths to change the radiation angle in the longitudinal direction with the same grating antenna. This work indicates that wide 2D image-scanning could be achieved with the 1D phased-array.

In this paper we design the 1D phased-array antenna to attain wider and more efficient beam-forming with the grating

structure. We also design a new type antenna using the nano-metallic antenna based on the surface plasmonics and their performances are compared with those of the grating antenna.

II. DESIGN AND SIMULATION

In the photonic phased-array antenna, a wide-angle beam-steering is required for 3D image scanning in the LiDAR system. For this purpose, a single antenna should radiate the light wave in a large angle enough to cover a wide scanning range. The radiation angle ($2\theta_r$) of a single antenna can be roughly estimated with following equation:

$$2\theta_r = \frac{2\lambda_0}{\pi W_r}, \quad (1)$$

where λ_0 is the operational wavelength and W_r is the width of antenna. From this relationship, the width of antenna should be smaller than the wavelength scale as possible. The Si-photonic technology based on silicon-on-insulator (SOI) wafer can be a solution to achieve a small photonic antenna and a narrow waveguide due to high refractive contrast, near $\Delta n \approx 2$, between the silicon core and the oxide cladding [3]. Thus we employ a single-mode waveguide for the phase-feeding line being connected to the antenna. The geometry of the waveguide is set with a width W in a range of 300 nm ~ 500 nm and a thickness h of 250 nm for a selected wavelength λ_0 of 1550 nm.

In the arrayed antenna, the beam-steering angle ψ_{steer} can be decide as following equation [2]:

$$\sin \psi_{\text{steer}} = \frac{\Delta\phi}{2\pi} \cdot \frac{\lambda_0}{d}, \quad (2)$$

where d is the array pitch and $\Delta\phi$ is the phase difference between neighbouring antennas. From the relations given in Eqs. (1) and (2), the steering angle can be extended with a narrow element antenna and a narrow lateral spacing of the antenna array. On the other hand, to increase the far-field resolution, we need to increase the number N of the element antennas in the array. The divergence angle ψ_{div} of a coherent beam emitted from the array, defined by the full-width of half-maximum of the field, can be estimated by following equation [4]:

$$\psi_{\text{div}} \approx \frac{0.886\lambda_0}{Nd \cos \psi}. \quad (3)$$

A. Grating antenna

From a single grating antenna, the longitudinal radiation angle θ , defined by the angle from the normal direction toward

the longitudinal direction of the grating, can be estimated by following equation based on the diffraction theory [2]:

$$\sin\theta = \frac{\Lambda n_{eff} - \lambda_0}{n_c \Lambda} \quad (4)$$

where Λ is the period of grating, n_{eff} the effective refractive index of the grating, n_c the refractive index of cladding. However, when the grating and the waveguide scale is comparable or smaller than the diffraction limit, as the structure designed in this work, the detailed radiation pattern can be analysed through numerical simulation rather than the equations based on the diffraction theory. Thus we designed the antenna structures using Lumerical FDTD tools [5].

Fig. 1 shows the schematics of basic structure of the waveguide and the single grating antenna and simulated far-field patterns. The waveguide is designed on a SOI structure with a top silicon thickness of 250 nm and a buried-oxide thickness of 2 μm . The rib waveguide is used with a waveguide width w of 1 μm and a slab height of 100 nm for single-mode operation, as shown in Figs. 1(a) and (b). The grating antenna is located at the end of rib waveguide with a period Λ of 620 nm, a etch depth of 90 nm and a duty ratio of 50%, as shown in Fig. 1(c). The incident light is given with an operational wavelength of 1550 nm and a TE-like polarization, as appeared in Fig. 1(b). From the simulation result of the output far-field, shown in Fig. 1(d), the maximum radiation range is over 50° to ψ -axis. This result indicates that the designed grating structure can be applied to a phased-array for a wide beam-steering.

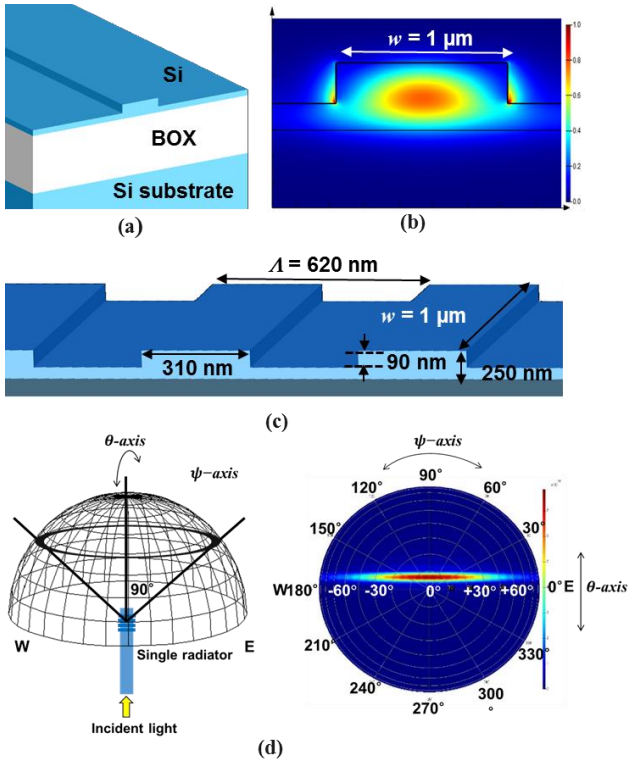


Figure 1. Schematics of designed grating structure and FDTD simulation result: (a) rib waveguide structure, (b) single-mode field distribution in waveguide, (c) grating antenna structure, and (d) simulated output far-field pattern.

Based on the grating antenna structure designed in Fig. 1, the performances of the phased-array antennas is simulated varying the number of grating antennas ($N = 8, 16, 32$) for a fixed length $L_g = 15 \mu\text{m}$ and also changing the length of grating antenna ($L_g = 10 \mu\text{m}, 12.5 \mu\text{m}, 15 \mu\text{m}$) for a fixed grating number $N = 8$, as illustrated in Fig. 2(a). To minimize the evanescent mode coupling between the waveguide arrays, the gap distance w_g of adjacent waveguide is determined to be 0.5 μm , as shown in Fig. 2(a). Then, the array pitch d becomes to be 1.5 μm . From this array pitch, the maximum steering angle ψ_{steer} can reach $\sim 85^\circ$, as estimated from Eq. (2). Fig. 2(b) shows the influence of the grating number. Increasing the number, the divergence angle ψ_{div} to the lateral direction of the output far-field is decreased and it can reach 1.2° with $N=32$. Fig. 2(c) shows the influence of the grating length. Another divergence angle θ_{div} to the longitudinal direction of the output far-field is decreased and it can reach 3.3° with $L_g=15 \mu\text{m}$. If the side lobe of output beam is appropriately suppressed, we can achieve a far-field resolution of about 1.2° (ψ) $\times$ 3.3° (θ) from array with $N=32$ and $L_g=15 \mu\text{m}$.

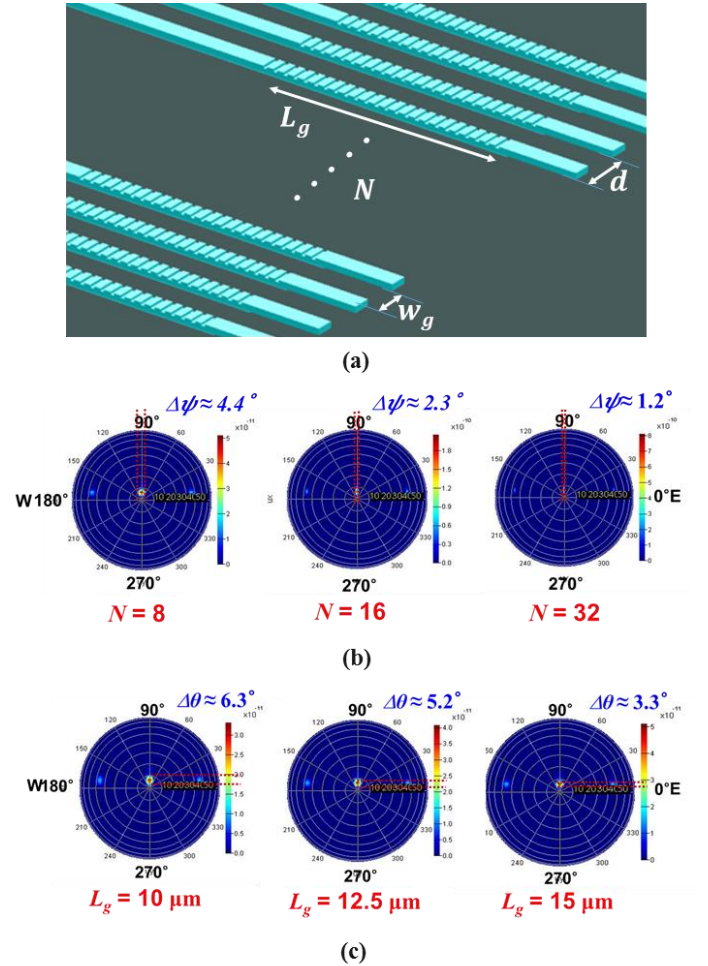


Figure 2. Schematic of grating antenna array and FDTD simulation result: (a) structure of phased-array antennas, (b) simulation results of output far-fields for various numbers of antennas ($N = 8, 16, 32$), and (c) of output far-fields for various lengths of antennas ($L_g = 10 \mu\text{m}, 12.5 \mu\text{m}, 15 \mu\text{m}$).

Beam-steering performance is simulated for a grating phased-array with $N=8$ and $L_g=15\text{ }\mu\text{m}$ by changing the phase difference $\Delta\phi$. Fig. 3 shows the beam-steering features with three phase differences $\Delta\phi$ of 0° , 180° and 240° . This simulation results indicates that the designed phased-array can provide a wide beam-steering over $\pm 42.5^\circ$ assigning a full phase difference.

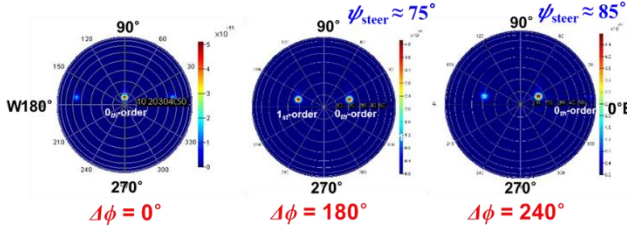


Figure 3. The FDTD simulation result for the beam-steering performance of the grating phased-array by changing the phase difference with $\Delta\phi = 0^\circ$, 180° and 240° .

B. Nano-metallic antenna

Here, we propose a compact metallic nano-antenna loaded on a single-mode waveguide, as shown in Figs. 4(a) and (b). A gold layer with a thickness $t=120\text{ nm}$ and $L=250\text{ nm}$ is coated onto the waveguide at the antenna region. We consider the transverse electric (TE) guided mode, as plotted in Fig. 4(c) for $W=350\text{ nm}$, $h=250\text{ nm}$. The guided mode is loaded into the metallic nano-antenna and then radiated toward free-space. Fig. 4(d) shows simulated result of the near- and far-field profiles of the nano-antenna for the y-polarized electric field in y-z plane. The fields in Fig. 4(d) shows a wide radiation over 90° occurs from the nano-antenna section.

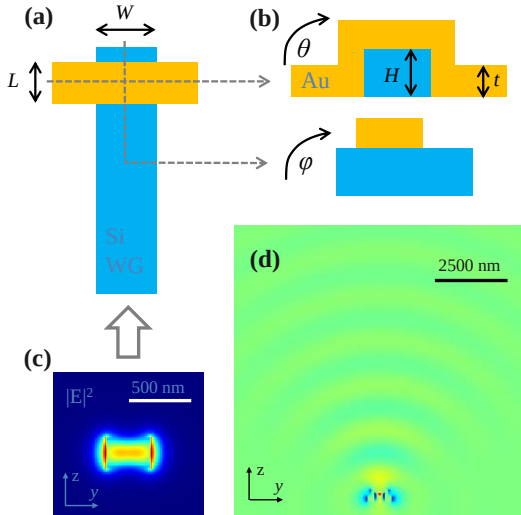


Figure 4. Schematics of a nano-metallic antenna loaded on the waveguide and simulation results of the confied and radiated fields: (a) top-view and (b) cross-sectional view of the metallic antenna, (c) electric field distribution of a guided TE mode in the waveguide, (d) near- and far-field profiles of y-polarized electric field radiated from the metallic antenna.

Fig. 5(a) shows the radiation efficiency of the single nano-antenna as a function of wavelength. There are two peak wavelengths within the wavelength range between 1400 nm

and 1700 nm . At these wavelengths, the incident mode from the waveguide can be coupled to the nano-antenna mode. On the first resonance wavelength at 1530 nm , selected for example, the light is tightly confined at the metal-dielectric surface, as shown in Fig. 5(b). Such resonance is resulted from the surface plasmon polaritons at the metal-dielectric interface.

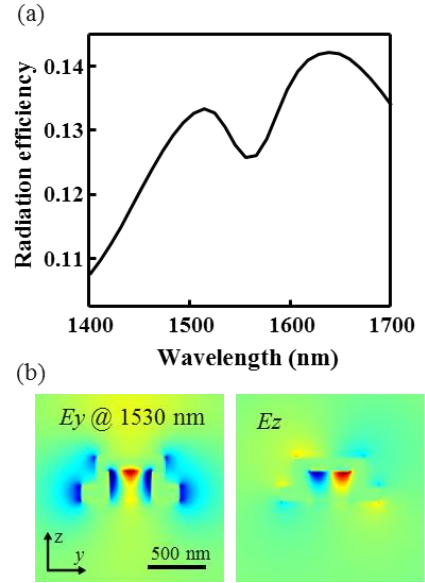


Figure 5. (a) Radiation efficiency of the metallic antenna and (b) electric field profile near the antenna core of a single nano-antenna loaded on the single-mode waveguide.

Beam-steering performance is simulated for a phased-array based on the nano-metallic antenna with $N=16$ and $d=800\text{ nm}$ by changing the phase difference $\Delta\phi$. Fig. 6 shows the structure of the nano-metallic antenna and the beam-steering features obtained from the change of the differences in a range of $-\pi/2 \leq \Delta\phi \leq +\pi/2$. This simulation results of Fig. 6(b) indicates that the designed nano-metallic phased-array can provide a wide beam-steering over $\pm 45^\circ$.

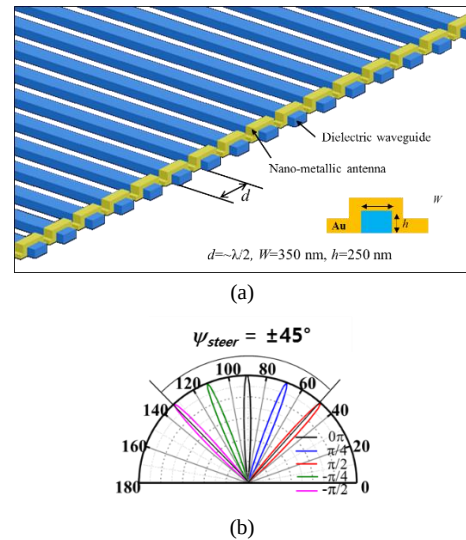


Figure 6. (a) Schematic of a nano-metallic antenna array and (b) simulation result for the beam-steering performance by change the phase difference.

III. DISCUSSION

From both of the grating antenna array and the nano-metallic array designed in this work, the beam-steering performance are simulated and achieved about $\pm 42.5^\circ$ (lateral direction) with the number of antennas ($N = 8$). The proposed nano-metallic antenna shows a strong potential for the 2D antenna array applications with its compactness ($L=250$ nm) than grating antenna ($L_g > 2.5$ μm). However, at the 1D antenna array, grating has an advantage for decreasing longitudinal divergence angle, which can make high-resolution beam scanning, with controlling of its length contrary to nano-metallic antenna. The proposed structures can be applicable to various applications such as high resolution beam scanning and densely integrated array due to their directional beam-forming and small footprint.

IV. CONCLUSIONS

We have proposed nano-photonic phased-array antennas suitable for wide-angle beam-steering. Two types of the antenna based on the grating structure and the plasmonic metal thin film were designed using a finite-difference time-domain simulator. From both types of the phased-array, the simulated radiation performances shows possibility of wide beam-steering over 85° to lateral direction. The designed nano-metallic antenna has a quite small scale within a half wavelength so that it is more suitable to extend the steering range and also to achieve two-dimensional array.

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